AALTO UNIVERSITY

SCHOOL OF ELECTRICAL ENGINEERING

Department of Electrical Engineering and Automation

Adrian Mateos

Improving Well-being in Office Buildings through Lighting

Thesis submitted for examination for the degree of
Master of Science in Technology.

Espoo 1.1.2019

Thesis supervisor: D.Sc. (Tech.) Paulo Pinho

Thesis instructor: D.Sc. (Tech.) Henri Juslén

AALTO UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING Abstract of the Master's Thesis

Author: Adrian Mateos

Title: Improving Well-being in Office Buildings through Lighting

Date: 1.1.2019 Number of pages: 56 + 11

Department of Electrical Engineering and Automation
Major: Translational Engineering Code of major: ELEC3023

Supervisor: D.Sc. (Tech.) Paulo Pinho
Instructor: D.Sc. (Tech.) Henri Juslén

Three ongoing changes are pushing new kind of lighting to offices: a society-wide trend of well-being, new research on the effects of lighting on well-being and the constant development of technology. While these changes are beneficial and improvements on well-being are welcome, the fast pace leaves key people, such as lighting designers and office managers, without tools and susceptible to bad practices. Designers may have to rely either on old word or unreliable sources, because standards, the usual guidebooks, have a hard time keeping up with the changes. Managers may not know how to deploy well-being to their offices and may trust whatever the market is offering them.

This thesis aims to give lighting and interior designers and office managers tools to critically implement well-being through lighting. It describes the three ongoing changes in detail, discusses the shortcomings of standards and proposes a practical guide for gradual improvement of well-being in the office environment. The aim is pursued in two ways: first, by conducting a literature study for the relevant theory and second, by conducting three case studies to get a practical point of view. The case studies were done by conducting lighting measurements and assessments in three different office environments.

The results suggest that there is need for new de jure lighting standards. They should put more emphasis on the non-visual effects of light, and instruct how current lighting technology, such as sophisticated control, can help in improving well-being. While de facto standards from certifiers are ahead on these aspects, their advice should be taken with a grain of salt, as eventually they are market-driven. Furthermore, the case studies revealed points for improvement regarding well-being, even in offices with relatively modern office lighting. A low red color rendering index R9 and the low reflectance of furniture surfaces were the most prominent common issues for the offices. These points were then used together with the theory from the literature study in composing the guide for gradual improvement.

Keywords: lighting, well-being, wellbeing, standard, office

AALTO-YLIOPISTO
SÄHKÖTEKNIIKAN KORKEAKOULU

Diplomityön tiivistelmä

Tekijä: Adrian Mateos

Työn nimi: Hyvinvoinnin parantaminen valaistuksen avulla toimistorakennuksissa

Päivämäärä: 1.1.2019 Sivumäärä: 56 + 11

Sähkötekniikan ja automaation laitos
Pääaine: Translationaalinen tekniikka Pääaineen koodi: ELEC3023

Valvoja: TkT Paulo Pinho
Ohjaaja: TkT Henri Juslén

Kolme ajankohtaista muutosta ajaa toimistoihin uudenlaista valaistusta: yhteiskunnallinen hyvinvointitrendi, uudet tutkimukset valaistuksen vaikutuksista hyvinvointiin ja tekniikan jatkuva kehittyminen. Vaikka muutokset ovat hyödyksi ja hyvinvoinnin parantaminen tervetullutta, muutosten nopean tahdin vuoksi avainhenkilöillä, kuten valaistussuunnittelijoilla ja toimistojen johdolla, ei ole uusimpia työkaluja käytettävissään, ja he ovat alttiita vääränlaiselle käytännön tiedolle. Suunnittelijoiden täytyy luottaa vanhoihin käytäntöihin tai epäluotettaviin lähteisiin, koska standardit, jotka yleensä ohjaavat suunnittelua, eivät pysy muutoksen perässä. Yritysten johto ei välttämättä tiedä kuinka edistää hyvinvointia toimistoissaan, ja he saattavat luottaa siihen, mitä markkinat ikinä tarjoavatkin.

Tämä diplomityö pyrkii tarjoamaan valaistus- ja sisustussuunnittelijoille sekä yritysten johtajille työkaluja hyvinvoinnin edistämiseen valaistuksen avulla. Se esittelee yksityiskohtaisesti edellä mainitut kolme muutosta, käsittelee standardien puutteita ja esittää käytännönläheisen oppaan hyvinvoinnin asteittaiseen parantamiseen toimistoympäristössä. Tavoitteeseen pyritään kahdella keinolla: ensin luodaan oleellinen teoriapohja kirjallisuuskatsauksen avulla, sitten etsitään käytännön näkökulma tapaustutkimuksilla. Tapaustutkimusta varten suoritettiin valaistus-mittauksia ja -arviointeja kolmessa erilaisessa toimistoympäristössä.

Tulosten perusteella uusille de jure -standardeille on tarvetta. Niiden tulisi korostaa valon ei-visuaalisia vaikutuksia, ja ohjeistaa hyvinvoinnin edistämisessä nykyaikaisella valaistus-tekniikalla, kuten esimerkiksi moderneilla ohjausjärjestelmillä. Vaikka sertifioijien de facto -standardit ovatkin edellä näissä asioissa, niiden ohjeisiin tulee suhtautua kriittisesti, sillä niitä kuitenkin luodaan markkinalähtöisesti. Lisäksi tapaustutkimus osoitti toimistoissa olevan useita parannuskohteita hyvinvointiin liittyen, jopa niissä, joissa oli suhteellisen moderni valaistus. Matala punaisen värin värintoistoindeksi R9 ja tilojen kalustuksen pintojen matala heijastuskerroin olivat merkittävimmät toimistoille yhteiset ongelmat. Näitä tietoja käytettiin yhdessä kirjallisuuskatsauksen teorian kanssa asteittaisen parannusoppaan laatimiseen.

Avainsanat: valaistus, hyvinvointi, standardi, toimisto

Preface

I want to thank

Henri for his general open-mindedness, professionalism and curiosity in life, which serve as an example for everyone.

Paulo for his combination of professional pedantry and warm people skills, which together with his patience make him an exemplary teacher.

Silva for her endless support and love.

My friends and family, for doing the friends and family things that everyone needs.

And finally, myself for finishing this damn thesis.

Helsinki, January 1st, 2019

Adrian Mateos

Table of contents

Symbols and abbreviations

AI	artificial intelligence
ASTM	American Society for Testing and Materials
BLE	Bluetooth low energy
BREEAM	Building Research Establishment Environmental Assessment Method
cd	candela
CEN	European Committee for Standardization (*Comité Européen de Normalisation*)
CENELEC	European Committee for Electrotechnical Standardization
CIE	International Commission on Illumination (*Commission Internationale de l'Enclairage*)
DALI	Digital Addressable Lighting Interface
DSE	display screen equipment
EA	European co-operation for Accreditation
EU	European Union
EML	equivalent melanopic lux
ETSI	European Telecommunication Standards Institute
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ipRGC	intrinsically photosensitive retinal ganglion cell
ISO	International Organization for Standardization
ITU	International Telecommunication Union
LED	light-emitting diode
LEED	Leadership in Energy and Environmental Design
lm	lumen
lx	lux
m	meter
NSB	national standards body
PIR	passive infrared
PoE	power over Ethernet
SAD	seasonal affective disorder
sSAD	subclinical seasonal affective disorder
SDO	standard developing organization
SME	micro, small and medium-sized enterprises
UGR	unified glare rating
W	watt
WTO	World Trade Organization

1. Introduction

Well-being is a trend that is changing the society. Ever more people are interested in increasing the quality of their life and having more energy by pursuing a higher level of well-being. The trend reaches outside the traditional view of being either healthy or sick and focuses more on prediction and prevention, rather than just treatment. [1], [2] The pursuit of well-being spreads to many fields in life, including work, where managers start to believe and understand the benefits of employee well-being. Besides policies and attitudes, improving the physical work environment leads to better well-being.

An important part of the everyday working environment is light, which is traditionally known to increase efficiency, safety and comfort. There is plenty of research about the various effects of light on people [3]-[5] and how lighting affects employees at work [6]-[10]. A significant change in the understanding of these effects happened in the beginning of the millennium, when a certain photoreceptor (ipRGC) was discovered in the human eye. After this finding light has been shown to have an impact on various physiological aspects such as the circadian rhythm, alertness and even depression. [5] All these effects of light play an important part in human well-being,

There is also another, ongoing change related to light; the evolution of lighting technology. The advancements of light emitting diode (LED) lighting have made it easy to fine-tune the lighting conditions [11], which can be automated by using sophisticated control systems and equipment, such as sensors [12]. Storing and analyzing the vast amount of data gathered by sensors and control interfaces is potentially leading to an even bigger change. A smart system that learns from the users' actions and can control lighting according to their preferences and moods is likely to have an impact on well-being. [13]

These three changes, the trend of well-being, the discoveries of the effects of light and the technological advancements in lighting encourage employers, building owners and designers to create spaces where lighting boosts well-being. This begs the question: how to create such an environment? While companies can work on their own to find out, technical standards created in consensus are an important source of information and a base for credibility for lighting designers. But can standards keep up with the change? In previous research, this question has been studied for the case of medical technology [14], [15], but for lighting such studies do not appear to exist.

This thesis aims to fill this gap for its part and participate in the discussion by presenting how the current lighting standards take well-being into account. It also speculates how and why the standards should be improved to match the level of newest research and technology. Furthermore, this thesis attempts to help in creating office environments of well-being by extracting the most relevant and feasible information from current standards and studies and using it to compose a guide for gradual improvement. To add a more hands-on view and gain understanding on possible practical issues, three case studies are conducted, where lighting measurements and assessments are performed in three different office environments.

This thesis is structured in the following way. This first chapter establishes the motivation for the thesis and introduces its topics. The second chapter is a literature study, which presents the current situation and future of lighting technology in office buildings, clarifies the definition of well-being and how lighting affects it, and finally introduces relevant building standards. The third chapter covers the case studies of three office buildings. In the fourth chapter the office standards and the results of the case studies are discussed, the office well-being improvement model is composed and ideas for future studies are proposed. Finally, everything is concluded in chapter five.

2. Literature study

This chapter presents the current situation of the topics covered in this thesis. It is a literature review that serves as a basis for discussion about how office lighting and well-being are currently considered in prevalent standards, and what should be done differently. The contribution of this thesis in the discussion is presented in chapter 4.

In the first subchapter, today's technologies and trends in office lighting are addressed. The second subchapter defines well-being and discusses its state. The third one introduces the pertinent building standards that consider lighting in buildings.

2.1. Lighting in office buildings

To assess the relationship between well-being and lighting in a modern office environment, it is important to cover the current technological state of lighting, and what is expected to change in the future. Furthermore, an overview of lighting in the contemporary office may help the reader put the theory into a context and put the information into practice.

This subchapter is divided into three parts: first it addresses the current lighting technology in general, then shows what the near future for lighting most probably looks like, and finally, how these technologies apply to the modern office environment.

2.1.1. Prevalent lighting technology

Light-emitting diodes are on their way in becoming the dominant building lighting technology, as can be seen from Figure 1 [16], [17]. LEDs are semiconductor light sources, and their principle was introduced already in 1907 [18], but they have only been used in minor applications since the 1960s [19]. However, during the last decade, LED technology has been quickly replacing fluorescent luminaires for several reasons. The luminous flux per watt (efficacy, lm/W) of LEDs is higher and they have a longer lifetime. Furthermore, they can be flexibly embedded to various structures. [19]

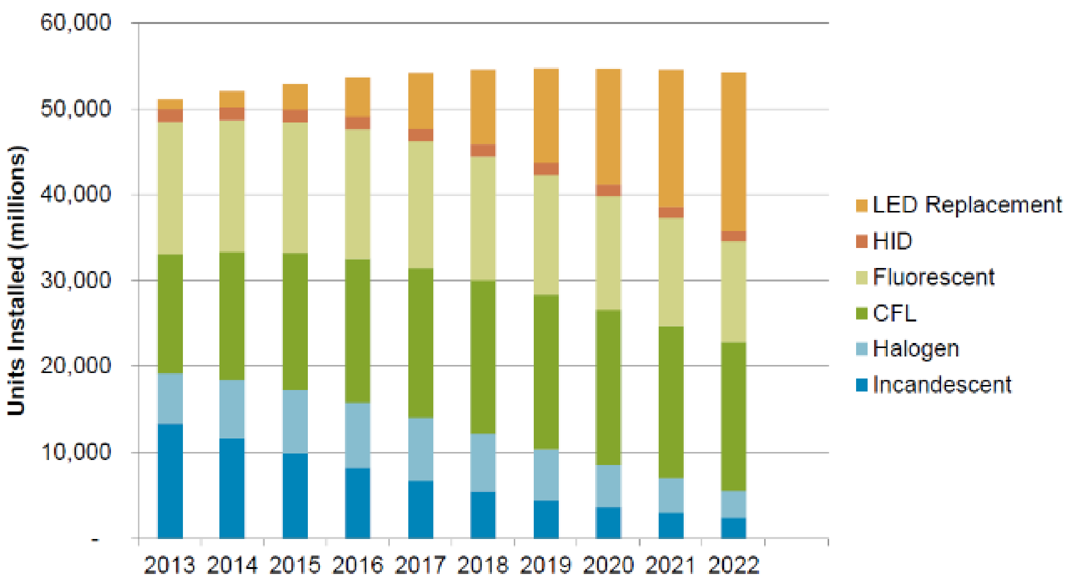

Figure 1. Evolution of the Global Installed Lamp Base by Lighting Technology [16], [17].

One of the most significant practical advantage of LEDs in comparison to other high-efficiency lighting technologies (fluorescent, high-intensity discharge, plasma) is the superior controlling possibility. The key factor for better control is dimming, which for LEDs is simple to implement and quick to execute. The other technologies suffer from challenges under dimming, such as reliability and lifetime issues and longer response times. Besides decreasing the energy consumption and increasing the reliability of LEDs, dimming considerably enhances user experience. It is more practical and comfortable to gradually change the light levels than to abruptly switch lights on and off. Dimming also allows users to fine-tune the lighting conditions by precisely changing light levels, colors and color temperatures. [11], [20] Interestingly, the efficacy and lifetime of LEDs increases as they are dimmed down [12].

How is LED lighting controlled then? Basic control methods include the use of switches, dimmers and timers. Manual wall-mounted switches work by closing and opening the electrical circuit to turn the lights on and off. Manual dimmers, which may be integrated to the switches, control the LED driver and are used to gradually adjust the light level. Timers are used to automatically switch the lights at designated times. [12]

Another way to control lighting is through sensors, which allow the automatic adjustment of lighting according to selected physical phenomena, such as movement. They are being used to achieve energy savings and improve user experience. Good examples are occupancy and vacancy sensors, which utilize PIR (passive infrared) or ultrasonic technology. They reduce the time lights are unnecessarily on, and typically spare the user from having to interact. Movement sensing may also be used for security purposes. Another common type of sensors are photosensors, which are used to detect the light level of the space. This way they can be used to save energy by controlling the lighting according to present natural light. [12] Sensors are becoming more common hand in hand with LED technology, and while the main motivation for implementing them has been energy savings, the way they may benefit human comfort is becoming increasingly important [20].

The signals from sensors, user interfaces and other controls have to be somehow transmitted to the luminaires. Initially this was done analogically using a standardized wired protocol called 0–10 V DC [21]. However, it has been replaced by a multitude of both wired and wireless digital communication protocols, which make installation and modification easier. A widely-adopted example of a successor for the analog control protocol is DALI (Digital Addressable Lighting Interface), which has been designed solely for lighting. [21].

DALI deserves a closer look given its prevalence in the lighting industry. A lighting manufacturer consortium developed the first version in the late 1990s [22]. It has since been revised many times [23], now being an open and international standard that allows component interchangeability between different equipment manufacturers [24]. DALI systems use a 2-wire bus for bi-directional communication between the controls and luminaires [25]. The bi-directionality allows effective report querying from all the devices and makes diagnostics easy [24]. The bus is powered for both the communication and powering up some smaller control devices, such as buttons and sensors. As the name suggests, DALI commands can be addressed to one or more devices, which allows flexible grouping and re-grouping without modifying the wiring. [25], [26]. Different luminaire dimming levels and scenes may be programmed into the system [25]. A DALI system can be configured to work on its own, or it can be integrated to a building level control system [24].

2.1.2. The future of lighting

As in other industries, new innovations spread to the field of lighting as processing power increases, algorithms get better and microprocessors get cheaper. New information and communication technologies allow for fundamental changes that shape the way how lighting and luminaires may be used. More and more luminaires also embed sensors, which makes it easier to flexibly control each individual luminaire. Furthermore, the sensors provide valuable data, which when combined with better connectivity and processing may be used in various smart applications, that are not necessarily related to lighting. [20], [27]

Emerging lighting control systems include both wireless and wired communication between luminaires, sensors and controllers. Especially the wireless technology has evolved quickly and is making its way to the industry. The controlling in both systems may be either distributed or centralized; in distributed control all the nodes may either operate by themselves or in cooperation with the others, whereas the nodes of a centralized system follow a central master node [27]. Furthermore, the physical or logical network may be arranged in several ways, called network topologies [24]. Some examples of network topologies are shown in Figure 2.

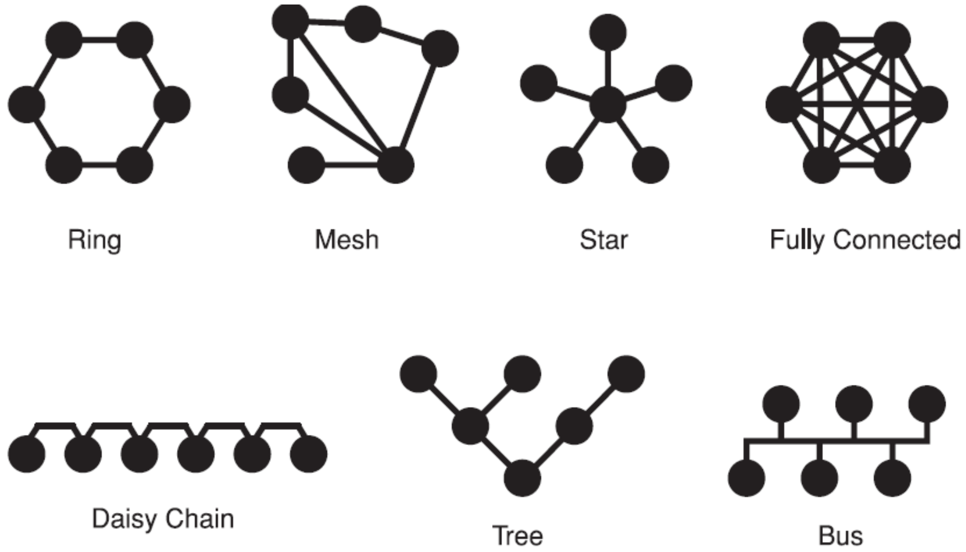

Figure 2. Examples of network topologies [24].

Wired systems

Wired control usually passes through a physical cable that connects all the devices, and the network topology is often a daisy chain or a star. As usually is the case with digital and analog technology, digital wired control has overcome the traditional analog systems. Digital technology is more reliable, allows a higher bandwidth and is easier to install. [21]

The well-established DALI technology is also going through a change; a successor was lately introduced, called DALI-2. The backwards compatible new version of the standard demands more device testing from the manufacturers. Moreover, DALI-2 products require testing by a third party, unlike the previous one. The new standard also specifies the control devices connected to the DALI bus, further increasing the compatibility between the products from different brands. [23], [26]

A good example of a relatively new trend in wired lighting is Power over Ethernet (PoE). PoE is a standard under IEEE 802.3 (Institute of Electrical and Electronics Engineers), and it allows transferring both data and power through an Ethernet cable. This technology suits very well for LEDs, which require low power. The luminaires connect to a central hub, which is a part of the IT network, and no separate control cabling is required. Thus, control and data collection can be easily integrated to other systems. The drawback of PoE are the large losses caused by the low voltage, which limits the distance between the luminaires and the hub. [22], [27]

Wireless systems

In wireless systems, the commands and data move by radio waves instead of a physical cable. Naturally, the wire material costs for a wireless system are smaller than for a wired one [21]. In retrofitting situations, where an old lighting system is replaced by a new one, a wireless lighting system is easier and less disruptive to deploy than a wired one [28]. In new buildings, the lack of communication wiring significantly reduces the installation costs on areas that are difficult to wire and makes future layout changes easier [21].

An important thing to consider is the wireless medium between the radio nodes. While packet losses are inherent to wireless technology, the medium may increase them [28]. Furthermore, the signal range may be significantly reduced if there are obstacles on the way of the signal [21]. Interference from other wireless signals may also affect the communication in the wireless system [22].

The network topology for wireless systems in office lighting is often a mesh network, in which the radios in each luminaire (and sometimes control device) communicate with each other. They all act as a repeater for messages, which improves communication reliability, since a failure of a single device does not stop the message. However, the mesh topology has the disadvantage of having more communication traffic and longer delays than a more traditional star configuration. The traffic is reduced by limiting the hop count of the messages. [28] Bluetooth low energy (BLE) mesh is an example of a wireless mesh protocol [22].

Another topology option for a wireless system is star, where the whole network is controlled through one central hub. Every other device only communicates with the hub, which then broadcasts the message to all devices. [24] Wi-Fi is an everyday example of a wireless star-connected protocol [22]. This topology is also quite reliable, as a failure only affects a single device. [24] However, if the central hub stops working, the whole system may fail. [22]

Smart systems

Smart or intelligent systems, which by definition collect data and use algorithms and machine learning to improve efficiency and comfort, are making their way to the market. In the field of lighting, data gathered by movement sensors scattered around the building could be used to analyze and predict the need for light. Through self-learning the costs of commissioning would decrease, as the configuration of the system could be fully or at least partly automated. [13] Furthermore, the analytics from the sensor data can even be used in applications outside the traditional lighting industry [27], such as people flow prediction.

Lighting can work well as a standalone system but connecting it to the internet is becoming topical with the popularity of the Internet of Things (IoT). To allow the connection of other protocols than IP, a gateway is needed. A gateway works as a port to deliver data to and commands from cloud servers and back. The processing power and memory of the cloud may then be used to enhance the benefits of smart systems. Furthermore, internet connectivity makes it possible to remotely diagnose, configure and control the lighting system. [29]

Smart systems raise a question about security and whether the system could be accessed maliciously by an unauthorized party. Data encryption and security protocols are a usual way to protect any systems from unwanted usage. Wired systems are more secure than wireless in the sense that to access the network, a physical connection has to be established. However, for instance, BLE mesh access requires a short physical distance. Therefore, intrusions could be avoided by ordinary building security. [22] Yet, systems that are connected to the internet carry a risk of being remotely hacked, which should be taken into account on design. [30]

As artificial intelligence (AI) evolves, there may be concerns about the decisions made by the system itself. Again, these risks should be considered, and proper design is key. In lighting, the advantages of AI could outweigh the risks, as AI could help detect malevolent control schemes and suppress them based on abnormal operation of the system. [13]

Despite the possible problems, smart systems are developing fast. The autonomy of a smart lighting system and the data it provides will not only reduce costs, but also shift the focus to the users of the building. [13] The interest in the well-being of people has already grown in the industry, as the new technologies become available and new market opportunities arise. This has brought forth a term called "human centric lighting", which thrives to comply with natural necessities and to adapt to the preferences of individuals. [31] The relationship between lighting and well-being is covered in detail in subchapter 2.2. Well-being is also one of the forces driving change in office lighting, as is elaborated in the next subchapter.

2.1.3. Office lighting

Determinants in office lighting

Offices, spaces for knowledge work, have developed over time. The cubicle offices of the industrial era became open-plan offices, which have recently started evolving into multi-space offices. These offices of today combine different spaces for different kind of work; group work rooms, focus rooms and various meeting rooms for varying kind of conversations. Lounges, cafes and other social and comfortable spaces also make part of a modern office. Naturally, the evolution of the office does not only concern the layout, but also other design elements of the space, of which lighting is one. Two things mainly affect the lighting in offices: management policies and technology. [12], [32]

Managerial decisions are a driving force for changes in office lighting. In general, the managers want to create a working environment that ensures the best results and retains talent. This is done not only by illuminating work tasks properly, but also considering the comfort and personal needs of employees by allowing control over lighting. Moreover, as the different needs in business are often changing, flexibility is usually sought in the interior design, which applies to lighting as well. The office lighting also generally promotes the company culture to both staff and visitors. [12]

Along with management practices, there are two ways on how technology impacts office lighting. First, the technology that is being used by the people in the office. For instance, the lighting needed for writing on a typewriter and writing on a computer is quite different. Videoconferencing requires adequate lighting to enhance facial features, proper image projection and make it easy to take notes. Due to wireless communication, the employees are no longer tied to their desks, which requires suitable task lighting around the office. [12]

The second way is more straightforward; the current state of lighting technology, which determines what kind of products are available. The upgrade from fluorescent to LED lighting is an easy example of how new technology drives a change in offices. If a new technology is superior to an old one, it spreads out quite naturally, as the production of the old one stops.

Commonly used lighting technology in offices

In addition to LED luminaires, it is ever more usual to see sophisticated lighting control mechanics in modern offices. Occupancy sensors add comfort to sporadically used meeting rooms and luminaire-mounted sensors keep open-plan workstations lit only when they are being used. Photosensors allow daylight harvesting by dimming luminaires and controlling window shades as needed. [12]

The intensity, color temperature and color of office lighting may be controlled for varying type of tasks, providing flexibility. These parameters can be, for instance, scheduled to a daily rhythm. Preset lighting scenery can be triggered by other events as well, such as turning on a projector or monitor. Some systems allow individual control of each luminaire, enabling employees to tune the overhead lighting according to their preference and mood. [12] In some cases, mobile applications can be used to control lighting around the office [22].

For offices, as for many other types of buildings, DALI is a widely-established wired control method for building-level control. As the wireless technology is improving, wireless systems are making their way to offices, but they still cannot entirely replace wired ones. One possible alternative are hybrid solutions which combine both wireless and wired protocols. [22]

Collecting data through smart lighting systems is also becoming more popular in commercial buildings, including offices. Data analysis allows the optimization of space utilization and energy performance. [22] The self-learning capability of luminaires, which is improved by collecting data, is also starting to increase well-being in offices by anticipating the actions and preferences of the employees. [13]

2.2. Well-being

To be able to address well-being, the very concept and its components must be defined first. Being familiar with the various effects of lighting on people helps to understand the requirements of lighting standards and what kind of lighting should be pursued. Moreover, a detailed view may help and motivate the reader to seek and create positive lighting conditions in their own environment.

This subchapter clarifies the subject of well-being and introduces a definition that will be used in this thesis. Furthermore, the connection between light and well-being is explained in three parts: the physiological effects of light, the psychological effects of light and the psychological effects of actual lighting installations in offices. Finally, the effects are summarized by presenting the different media of influence on well-being.

2.2.1. What is well-being?

Human well-being may be approached in several scientific and philosophical ways. There are many different interpretations of the concept, and they have changed over time. In some instances, terms like quality of life, prosperity, poverty and happiness are used as synonyms to well-being. [33] Other definitions tie well-being to health, but the difference between them is not clear, as both contribute and affect each other [34]. However, it is outside the scope of this thesis to discourse all the different and complex views of well-being. For this thesis, well-being is defined in the following way: well-being refers to the various interconnected dimensions of physical, mental and social conditions, which extend beyond what is traditionally defined as health [35]. Furthermore, this view of well-being can be divided into a subjective and an objective dimension; the individual's experience of their life and the comparison of conditions of life with the social environment. The subjective dimension encompasses things like mood and feelings, whereas the objective dimension is related to things like health, education, social relationships, security and the surrounding environment. [34].

For a scientific approach, it is necessary to be able to measure well-being. The two dimensions of well-being are measured differently: subjective well-being is usually measured with self-reports, whereas objective well-being measurements are done through surveys [36], [37]. However, this thesis does not focus on direct measures of well-being as such, but instead on the measures of the parts that constitute well-being. The premise is, that improving the parts, whether of subjective or objective dimension, improves total well-being. That is, for instance, improving the mood or health of an individual improves their well-being.

Yet, there must be limitations on what to include in a thesis. With too wide a scope, most of any human action aims to improve well-being. Therefore, this thesis is limited to emphasize the aspects of lighting which are outside the more intuitive view of lighting benefits. These omitted intuitive benefits include traditionally accepted facts, such as visual performance and safety. Furthermore, energy efficiency and its influence on well-being is not discussed.

2.2.2. Effects of light and lighting on well-being

Lighting plays an important part in human well-being [38]. It allows people not only to see, but to act more easily, accurately and quickly, whereas poor lighting conditions may cause eye fatigue or headaches, even migraine. [3]. It is more comfortable to work and communicate when there is enough light, and lighting often contributes to safety. Lighting also helps to get the most out of visual aesthetics, and light itself may be used as an aesthetic element. [39] All these rather obvious regards have traditionally guided lighting design to provide visual performance and comfort and to improve the aesthetic appearance of the environment [40].

Light has also other, less straightforward effects on the human being. These can be divided into physiological and psychological effects[1]. In addition, lighting installations themselves may psychologically affect well-being. Next, these three effects are viewed in detail.

Physiological effects of light

Since 1834 it had been known that in the retina of the human eye there are two types of photoreceptive cells, called rod and cone cells, which are mostly responsible for receiving light. A physiological discovery made in 2002 augmented the view of how light affects humans. The new finding is a third kind of photoreceptor in the retina, called intrinsically photosensitive retinal ganglion cell (ipRGC). These photoreceptors regulate physiological effects in the human brain through impulses sent by a photopigment named melanopsin. The responsivity of ipRGCs depends on the wavelength of the light reaching them. Interestingly, as can be seen in Figure 3, the physiological sensitivity differs from the visual sensitivity of the eye (i.e. the sensitivity to different colors). While the peak sensitivity of the standard observer (V_λ) is 555 nm, the peak of the physiological response ranges from 447 to 484 nm. This is an important fact when considering different lighting conditions. [5], [6], [40]

[1] Also the effects in the previous paragraph fit into these categories, but they will not be repeated.

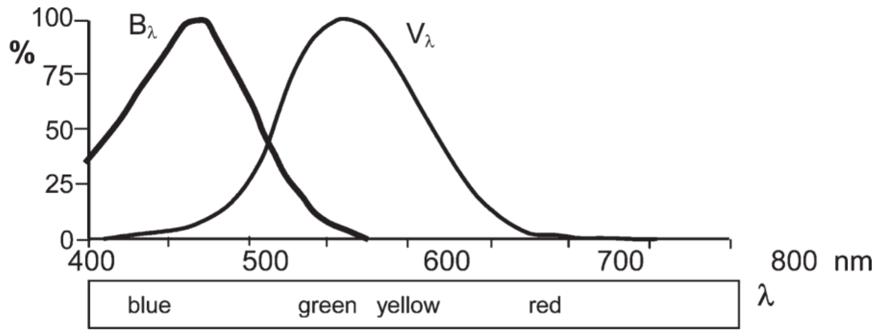

Figure 3. Spectral sensitivity of the physiological action of ipRGCs (B_λ) and the spectral sensitivity of (photopic) vision (V_λ) [6], [41].

The photopigment melanopsin sends impulses to a part of the brain named the pineal gland, which produces a hormone called melatonin [6], also known as the "sleep hormone" [42]. Melatonin, for its part, regulates the human physiological clock, which runs in periods slightly longer than 24 hours. That way the physiological and behavioral rhythms of the human body, called circadian rhythms, are synchronized with the environment. [4] Light captured by the ipRGCs, such as morning light, phase resets the endogenous sleep-wake rhythm. Thus, light affects indirectly most physiological, metabolic and behavioral processes in the human body. [5]

Furthermore, light affects the human body acutely by suppressing melatonin, which increases alertness. The illuminance level and the duration of light exposure increase the melatonin suppression; with long exposures, even moderate light levels may affect the circadian system. [3] Other acute effects include the increase in heart rate, body temperature and cortisol production, as well as the constriction of pupils. Light also increases both subjective and objective alertness, increases [sic] reaction time and reduces attention span. [5] Moreover, there is some evidence about light directly affecting mood and cognitive functions. [43].

In addition to these physiological effects, light helps in reducing depression, particularly in the case of seasonal affective disorder (SAD) and the subclinical version of SAD, sSAD. Light may also be used to treat sleep disorders related to the circadian rhythm, and circadian disruptions resulting from shift work, jetlag and space flight. Furthermore, light treatment for non-seasonal depression, bulimia nervosa, and problems related to menstrual cycles have been studied, as well as cognitive and fatigue problems related with chemotherapy, traumatic brain injury and senile dementia. [5]

A thing to consider is that with age, the human eye becomes slightly yellow, which filters incoming light. This significantly reduces the light received by the photoreceptors in the retina, especially at short wavelengths, as is illustrated in Figure 4. Thus, the neurophysiological processes are different for people of different ages. Older people, for instance, have a higher risk of sleep disturbances, as the circadian rhythm is not entrained properly. [40]

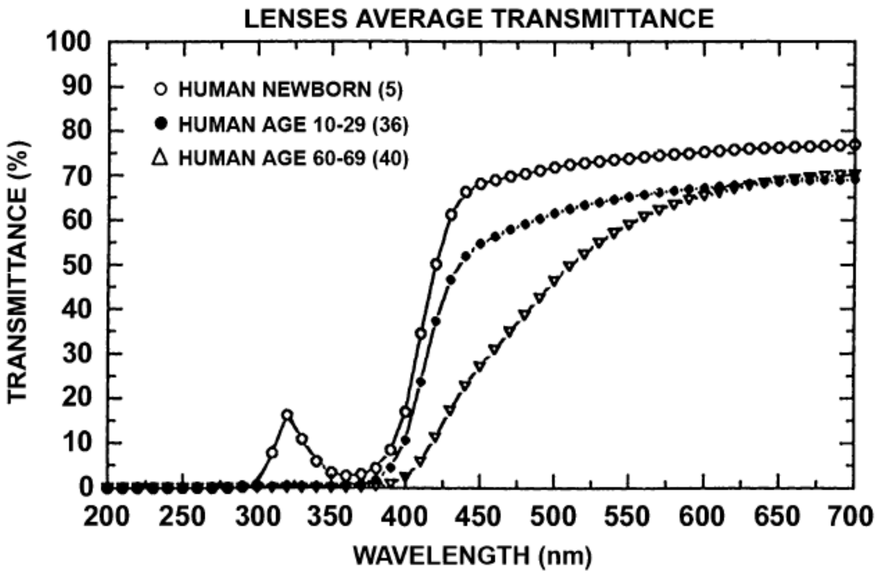

Figure 4. The average transmittance of human lenses at different ages [40].

Psychological effects of light

One rather obvious psychological effect of light is the negative emotions caused by visual discomfort. While the emotions depend on the viewer's culture and expectations as well as on the context, visual discomfort generally makes visual tasks harder, causes under- or overstimulation of the visual field, distracts or causes perceptual confusion. Examples of issues that cause discomfort are non-uniform lighting, glare, flicker, shadows and veiling reflections (e.g. when reading a shiny magazine page). [3]

There are also many complex psychological effects related to the perception of the environment, such as clarity, spaciousness and color appearance. [3] Without diving further into the dimensions of perception, the visual ambience has an impact on the feelings of people. Proper lighting positively affects memory, creativity, innovation and efficiency of decision making, and it also makes people more likely to help each other. [7] Self-oriented people improve their conflict resolution through collaboration in dim and warm lighting [44], and dimmer lighting promotes creativity [45]. Bright lighting in turn increases self-awareness and self-regulation [46].

Interpersonal relationships are another subject that lighting influences. Lighting affects the appearance of a person, which plays an important role in interpersonal perception and communication. The noise level on conversation also slightly shifts with lighting. Surprisingly, brighter surroundings result in quieter communication which also has an effect on interpersonal relationships. [7], [47]

Psychological effects of lighting installations

In addition to the psychological effects caused by light, people are also psychologically affected by the actual lighting installations. The installations form a part of people's everyday surroundings, and there are several mechanisms through which people are influenced by things in their vicinity.

When an existing lighting installation is changed to a newer one, the process affects people that are used to the older one. A change for the better usually makes people feel better, but there may also be resistance to change. The impact on people is determined by the way of managing the change process. [7] Improving the lighting conditions at a workplace by changing the lighting installation could also make the employees feel that their work is significant [7] and that they are cared about [48].

If the changes are done because the employees have complained about problems, or just wish for better, the positive psychological impact is slightly different. While it still gives a sensation of importance, it also generates the feeling of having control. This sentiment of autonomy is linked to job satisfaction, which in turn enhances well-being. Another lighting installation aspect that increases the feeling of autonomy is the possibility to control the lighting. [7] On the other hand, a control mechanism or a lighting installation that is not working the way it is expected may cause frustration.

New lighting installations can also trigger the so-called halo effect, in which positive presumptions about the lighting affect the performance of people. [7] Furthermore, knowledge about the impact of light could strengthen the presupposed effects.

While not actually a lighting installation, windows are another interesting psychological topic related to office lighting. In office environments, people tend to sit next to windows, but the full explanation for this is outside the scope of this thesis. Shortly put, windows provide variable light that allows to see well, but also a view-out. [3]

Summary of the ways of effect

To get a better view of the various ways through which light, lighting and lighting installations affect human well-being, they are concluded in Table 1. They have been divided into three groups: visual ergonomics, physiological aspects and psychological aspects. The visual ergonomics could be fit into the other two groups, but because the ways are under the traditional view of lighting, they are kept separate. The division into positive and negative ways is artificial, but it helps understand the effects. If the lighting affects through the same medium in both positive and negative ways (i.e. more light increases alertness, less light decreases alertness), only the more representative way is mentioned.

Table 1. The ways through which light, lighting and lighting installations affect human well-being.

	Visual ergonomics	Physiological aspects	Psychological aspects
Positive	Visual acuity	Alertness	Aesthetics
	Perception of space	Circadian rhythm alignment	Visual appeal of people
		Sleep quality	Feeling of control
		Cognitive functions (learning)	Halo effect
		Mood	
Negative	Errors	Headache/migraine	Distraction
	Eye fatigue	Stress (cortisol)	Perceptual confusion
			Overstimulation
			Understimulation
			Resistance to change
			Failure to meet expectations

2.3. Lighting standards for office buildings

To understand the current situation of standards related to office lighting, it is beneficial to know how standards are created in the first place. Insight into how standards relate to certification may give the reader tools to judge the usefulness of certification. Furthermore, knowing the differences between prevalent standards may help in deciding what path is smart to follow to implement well-being in practice.

This subchapter first explains what standards are, who develops them and how, and what are their upsides and downsides. Then, the connection between standards and certification is addressed. The last part introduces and compares common standards that relate to lighting in office buildings and sets out how these standards take well-being into account.

2.3.1. What are standards?

The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC), as well as The European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC) define standard as a *"document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context"*. These organizations also emphasize the optimization of benefits for the community. [49], [50] Other organizations, such as the European Commission and the World Trade Organization (WTO), have their own, similar definitions [51].

As the definition indicates, standards are made through collaboration of multiple parties that can compose or comment them. The stakeholders involved may include for example manufacturers, dealers, users, customers, researchers and regulators. In fact, liaison is the essential difference between standards and official regulations. Standards differ from regulations also in the sense that the usage of standards is voluntary. Still, many governments refer to standards in their legislation. Standards are open to everyone, whereas other technical documents may be designed for the use of a single company or group. [51], [52]

Virtually anything can be standardized; a product, a service or a system [53]. Standards can be grouped to: dimension systems, performance, methods/testing, management systems, symbols, terminology, products and "basic" standards (such as SI units). [51] It should be noted, however, that it is not fruitful to standardize everything, but rather be sure that standardization solves an actual problem [52]. For instance, things where personal preference or national secrecy is involved, should not be standardized [54].

There are many ways in which standards benefit companies, consumers and the society. Standards provide a common language for different parties and set requirements that add technical and economic value. They lower the barriers for new companies to enter the market and help to reduce transaction costs and risks in trade. They also facilitate communication and agreements between companies. Consumers' choices of purchase become easier when there is less variation and more compatibility. Standards also set a level of performance or safety, which is in interest of both the individuals and the society. Moreover, using standards in legislation reduces legislative work by providing frequently updated expertise and resources. [51], [52]

Standard types and their development

The recognized bodies mentioned in the definition are called standardization organizations. They can be divided into ones that are generally accredited by governments and others that are not. Accreditation means being recognized by and having a formal relationship with an authoritative party, such as a government. [51] In this thesis, the accredited standardization organizations are called *de jure (standardization) organizations*. Non-accredited organizations that develop standards are called *de facto (standardization) organizations*. The standards developed by de jure organizations are called *de jure standards* and the ones by de facto organizations are called *de facto standards*. De facto standards are also born when a method has become widely accepted over time, or when a company product has been extensively adopted throughout the market. This, however, is unlikely today, because technological advancements are becoming faster and more complex. [51], [54] The classifications are illustrated in Table 2.

Table 2. Classification of standards by standardization organization [51], [54].

Standard type	De jure	De facto	
Standardization by	De jure organization	De facto organization	"Practice"
Development method	Consensus	Consensus	Market dominance
Example of standard	ISO 3591:1977	DVD	VHS
Example of organization	ISO	DVD Forum (originally nine companies)	JVC (company)

De jure standardization organizations work at different levels: global, regional or national. The global de jure standards are created by ISO for general standards, IEC for electricity-related standards and ITU (International Telecommunication Union) for telecommunication-related standards. Respectively, the de jure organizations in Europe are CEN, CENELEC and the European Telecommunication Standards Institute (ETSI). These organizations work in cooperation with each other and other accredited organizations to avoid conflicting standards. [51] National level de jure organizations are called national standards bodies (NSBs) [54]. In Europe, the role of completely national standards is diminishing, and NSBs focus on working with the international organizations. In some countries, such as China and Japan, standardization is conducted by the government. [52]

The development of standards in de jure organizations is conducted by technical committees, sub-committees and working groups. The committees and groups are open for all member organizations of the de jure organization. After a proposal for a standard is approved, a draft standard is created, and each member may comment it. Then it is publicly consulted, and a vote is held. When consensus is found and the draft passes, the standard is published and implemented. Later, the standard may be reviewed regularly to keep it up to date. [51]

De facto organizations, in turn, are forums, consortia or so-called standards developing organizations (SDOs)[2]. The difference between forums and consortia is small, but essentially, they are groups of companies or organizations. They are usually formed to advance a particular technology, as in the case of DVD Forum, which originally consisted of nine manufacturers working on a successor technology for VHS. Forums and consortia differ from SDOs, which are organizations that focus mainly on standardization, such as IEEE and the American Society for Testing and Materials (ASTM). The standard development of de facto organizations is similar to the process of de jure organizations, where consensus of different parties is sought. [51], [54]

Issues with standards

While the benefits of standardization are apparent, there are some downsides, such as the problem with micro, small and medium-sized enterprises (SMEs). Their interests may not be sufficiently considered in the development of standards, as they could be underrepresented in the committees. Furthermore, the implementation of standards could cost them too much or be too complex. CEN and

[2] *Choi et al.* defines all organizations that focus on standardization as SDOs [54]. In this thesis, only non-accredited standardization organizations, that are not forum or consortia, are SDOs, which is the approach of *Bøgh* [51].

CENELEC are aware of this and have a standard writing guide to mitigate this problem by considering availability, costs and structure of the standard. [55]

Another issue concerns the speed of standardization. Sometimes old standards that are not updated could hinder product development and technological advancement [54]. Investing in new technology could be inhibited if standardization makes the previous technology life cycle longer than it would naturally be [56]. Some organizations, such as ISO and CEN work against this by reviewing their standards every five years [51], [54].

Despite the measures against the problems, wide consensus (quality) and fast decision making (speed) are contradictory. However, both do not have to be sought at once, but either can be emphasized depending on the case. For instance, standards considering health or the environment should focus on quality at the expense of speed. On the contrary, companies dealing with new technologies prefer quick decisions in order to boost innovation. [57] De facto standards, excluding the ones made by SDOs, are usually quicker to implement than those of de jure organizations, whereas de jure standards have higher credibility [54], [57].

2.3.1. Standards and certification

Another topic related to standards is certification. Certification means the procedure where a third party assures that a product, service or process meets specified requirements [58]. These requirements may be from specific standards, de jure or de facto [59]. In a sense, certification is communication between the supplier and buyer, with a third party in the middle, arousing more credibility. This third party is called a certification body or a certifier, and it either does the actual inspection of the product (or service, or process) itself or has another body do it. Whichever the method, the certification body is the one giving its word, a certificate, assuring the requirements are met. [60]

The complexity and costs of certification vary, depending on what is being certificated and what level of confidence is sought. Certification usually involves testing of product samples, but more intensive certificates may require more strict methods, such as production process inspection. If there is high demand for safety and reliability, the certification process may be more complicated, and therefore more expensive. [59]

Unfortunately, certification does not always guarantee that there is no conflict of interest. For instance, either the supplier or the buyer may have been involved in the setting of the standards against which the certification is done. This could make their business interests reflect on the standard, and therefore, the certification. Furthermore, the certification body itself may also have taken part on the standardization, or the standardization and certification could be done by the same body. This could cause ideological biases or even incentivize the certifier to make their process less strict, especially if significant money and competition is involved. [60]

As in the case of standardization organizations, accreditation is a way to increase trustworthiness. Certification bodies may be accredited by an authoritative body, which means getting an official evaluation by a governmental organization. [60] For example, in the European Union (EU), there is an accreditation infrastructure called European co-operation for Accreditation (EA) [61].

2.3.2. Lighting standards and well-being

There are several international and national standards concerning different aspects of lighting. Regarding this study, the most interesting ones are the standards about lighting in buildings. Only the standards that are in relatively widespread use in Europe are introduced here.

De jure standards: ISO and CEN

Among the most well-known is *ISO 8995:1:2002 (CIE S 008/E:2001) Lighting of work places – Part 1: Indoor*, which ISO has developed in collaboration with the International Commission on Illumination (CIE). In Europe, CEN has published *EN 12464-1:2011 Light and lighting. Lighting of work places. Part 1: Indoor work places*, which is also widely used. [62]

Even though there is almost a decade between the publication times of these two de jure standards, they are very much alike. Both entail design criteria on luminance distribution, illuminance, uniformity, glare, light directionality, colors, flicker, daylight and maintenance. They also include specific illuminance, glare and color rendering limits for different tasks and environments. The most significant differences are the guidelines to conducting measurements for illuminance, the introduction of a "background area" and new rules about display screen equipment. The newer standard also has stricter reflectance values, it introduces requirements for walls and ceiling and demands more from maintenance. However, minimum values on the surrounding area illuminance and shielding angles are less strict than on the older one. [63], [64]

ISO 8995:1:2002 and *EN 12464-1:2011* are almost identical from the point of view of well-being. For that reason, the well-being aspects of only the newer one are addressed here. *EN 12464-1:2011* confines its scope to entail requirements for visual comfort and performance of people with a *normal* visual capacity. Later, on a side note, it is mentioned that the visual performance of a person is affected by their visual capacity. However, the effects of visual capacity on visual comfort is not regarded. [63], [64]

In the lighting design criteria part of the standard, one of the three human needs that determine the lighting requirements is visual comfort (the other two are visual performance and safety). Visual comfort is elaborated to mean that the workers have a feeling of well-being, which indirectly increases productivity and work quality. The standard explicitly explains how different design criteria affects visual comfort. These criteria and the corresponding targets that should be fulfilled can be seen in Table 3, where also the ways through which the criteria affect well-being are presented. These ways are extracted from Table 1 in subchapter 2.2.2. and they are also included on the other tables about standard criteria further below. Note, that there are also other criteria in the standard which are not related to well-being, but visual performance and safety. They are not presented in the Table 3 to allow easier comparison with the other standards. [64]

Table 3. Well-being-related requirements of the standard EN 12464-1:2011 [63].

No	Criterion	Target	Affects well-being by increasing ↑ / decreasing ↓
4.2.	Luminance distribution	- Proper luminance distribution. - Bright enough surfaces, especially walls and ceiling.	↑ Perception of space ↓ Eye fatigue ↓ Distraction ↓ Understimulation
4.3.	Illuminance	- Proper illuminance and illuminance distribution.	↑ Visual acuity ↑ Perception of space ↓ Errors ↓ Eye fatigue
4.5.	Glare	- Proper UGR (unified glare rating) values.	↓ Eye fatigue ↓ Distraction
4.6.	Lighting in the interior space	- Lighting is not too diffuse. - Lighting is not too directional.	↑ Visual acuity ↑ Perception of space ↓ Perceptual confusion

			↓ Understimulation
4.7.	Color aspects	- High enough color rendering index. - Proper color temperature.	↑ Perception of space ↑ Visual appeal of people ↑ Aesthetics
4.8.	Flicker and stroboscopic effects	- Lighting has proper flicker properties.	↓ Headaches
4.9.	Lighting of workstations with DSE (display screen equipment)	- Proper luminaires to avoid screen reflections with high brightness. - Luminaires are located and arranged to avoid reflections with high brightness.	↓ Eye fatigue ↓ Distraction
4.12.	Additional benefits of daylight	- Daylight from windows should be used to supplement electric lighting. - Windows do not cause thermal or visual discomfort. - Windows do not cause loss of privacy.	↑ Visual acuity ↑ Perception of space ↑ Aesthetics ↓ Errors ↓ Eye fatigue
4.13.	Variability of light	- Variable lighting conditions.	↑ Alertness ↑ Circadian rhythm alignment ↑ Sleep quality ↑ Cognitive functions (learning) ↑ Mood ↑ Aesthetics

ISO is currently developing a new standard on lighting called *ISO/WD TR 21783 Light and lighting - Integrative lighting - Non-visual effects* and it is on a preparatory stage [65]. CEN is drafting a new version of *EN 12464-1*, which is forecasted to be released in 2020. However, it will not include health, and most likely neither well-being aspects. CEN is also working on another lighting standard, called *CEN/TS 17165:2018 Light and lighting - Lighting system design process*, which by the approved scope aims to promote well-being through the design process. [66], [67]

De facto standards: BREEAM, LEED and WELL

Besides the de jure standards there are several commercial certification bodies that have their own building certification programs. These certification bodies also act as de facto standardization organizations, and their certification programs follow their respective de facto standards. The most widespread of these programs are BREEAM (Building Research Establishment Environmental Assessment Method) with 565 000 certificated buildings or spaces and LEED (Leadership in Energy and Environmental Design) with almost 60 000. BREEAM was published in 1990 and LEED in 2000. Both programs focus on the environmental sustainability of buildings, and office lighting plays a small part in both. The certifications are achieved by fulfilling requirements from different categories in the standards, such as energy, material, waste and well-being. Points are then earned based on the type and amount of the requirements fulfilled, and the points determine the "certification level". Some of the requirements are mandatory, while other are optional. [68], [69]

The de facto standards behind the certifications are revised every few years. The current version of BREEAM includes three office lighting aspects in its Health and Wellbeing category: glare control, illuminance levels and lighting control. The criteria and their corresponding targets are presented in Table 4 along with the ways through which they affect well-being. BREEAM does not explicitly explain the well-being influence of the lighting aspects. [70]

Table 4. Criteria and targets of BREEAM that are related to office lighting [70], and the ways how they influence well-being.

No	MS*	Criterion	Target	Affects well-being by increasing ↑ / decreasing ↓
HEA 02	No (4)	Glare control	- Solar glare control without fully blocking sunlight.	↓ Eye fatigue ↓ Distraction
HEA 08	No (4)	Illuminance levels (Lux)	- Illuminance level compliance with national lighting guides or *EN 12464-1 Light and lighting - Lighting of workspaces.*	↑ Visual acuity ↑ Perception of space ↓ Errors ↓ Eye fatigue
HEA 09	No (4)	Lighting control	- Manually overridable daylight sensors. - Manually overridable infrared movement sensors. - Properly sized zones for different spaces.	↑ Feeling of control
*Is the requirement a minimum standard (i.e., mandatory)? Maximum credits in brackets.				

The requirements of the newest LEED, v4, are more detailed than BREEAM, but offer more flexibility. LEED includes office lighting in its Environmental Quality (EQ) category: interior lighting and daylight availability. The criteria and their corresponding targets are presented in Table 5 along with the ways through which they affect well-being. [71]

Table 5. Criteria and targets of LEED that are related to office lighting [71], and the ways how they influence well-being.

Cat.	PR*	Criterion	Target	Affects well-being by increasing ↑ / decreasing ↓
EQ	No (2)	Interior lighting	1. Enough adjustable lighting, separate control for presentations, control interface in the location of the controlled luminaires and with a line of sight to them. 2. Low enough luminance per angle, high enough color rendering index, enough direct-only overhead lighting, high enough reflectance on surfaces, low enough illuminance ratio between walls and work surface, low enough illuminance ratio between ceiling and work surface.	↑ Visual acuity ↑ Perception of space ↓ Errors ↓ Eye fatigue ↑ Feeling of control
EQ	No (3)	Daylight	- Proper amount of sunlight throughout the year.	↑ Alertness ↑ Circadian rhythm alignment ↑ Sleep quality ↑ Cognitive functions (learning) ↑ Mood ↑ Aesthetics
*Is the requirement a prerequisite (i.e., mandatory)? Maximum credits in brackets.				

From the point of view of this thesis, another, even more intriguing certificate is the WELL Building Standard (WELL in short form), which was introduced in 2014. It is quite new, and still less widespread than BREEAM and LEED, with a total of 100 certifications. The certificate is earned the same way as the other two, but WELL focuses solely on improving the human well-being in buildings. One of its categories is light, which plays a more extensive role in WELL than the others. [72]

A new pilot version of WELL is called WELL v2, and it was launched 31 May 2018 [72]. Because the work on this thesis was started long before that, and an extensive part of the work was done based on WELL v1, both versions will be described here. Their differences are also an interesting thing to consider.

WELL v1

The light category of the WELL Building Standard v1 consists of 11 features that can be applied to office lighting. Each feature is either a mandatory "precondition" to get the certification or a voluntary "optimization" which increase the level of achievement (silver, gold or platinum level). There are four preconditions (P) and seven optimizations (O), and each consists of one or more parts. Moreover, the parts may include several requirements. To earn the points from the feature, some parts demand the fulfillment of all the requirements, while others give a few alternatives among which to choose from. The requirements usually either demand meeting certain level of a physical quantity or describe how a system should work. The features and their corresponding targets are summarized in Table 6 along with the ways through which they affect well-being. [72]

Table 6. Office-related light features and targets of WELL Building Standard v1 [72], and the ways how they influence well-being.

No	P/O*	Feature	Target**	Affects well-being by increasing ↑ / decreasing ↓
53	P	Visual lighting design	1. High enough illuminance level on work plane, proper dimming and zoning of lighting, supplemental lighting available. 2. Low enough contrasts between visually adjacent surfaces and spaces.	↑ Visual acuity ↑ Perception of space ↓ Errors
54	P	Circadian lighting design	1. High enough vertical illuminance at eye level for long enough time.	↑ Alertness ↑ Circadian rhythm alignment ↑ Sleep quality ↑ Cognitive functions (learning) ↑ Mood
55	P	Electric light glare control	1. Luminaires have a high enough shielding angle for their luminance. 2. Luminaires at the top of the field of vision have a low enough luminance.	↓ Eye fatigue ↓ Distraction
56	P	Solar glare control	1. A system to prevent solar glare from low situated glazing. 2. A system to prevent solar glare from high situated glazing.	↓ Eye fatigue ↓ Distraction
57	O	Low-glare workstation design	1. Computer screens can be oriented to avoid indirect glare, overhead luminaires do not directly point at screens.	↓ Eye fatigue ↓ Distraction
58	O	Color quality	1. High enough color rendering index.	↑ Perception of space ↑ Aesthetics
59	O	Surface design	1. High enough reflectance of surfaces.	↑ Visual acuity ↑ Perception of space ↓ Fatigue

				↓ Distraction
60	O	Automated shading and dimming controls	1. An automated shading system. 2. Occupancy sensors and daylight sensors.	↓ Fatigue ↓ Distraction ↓ Feeling of control
61	O	Right to light	1. Proximity to view windows. 2. Proximity to exterior view windows or atria.	↑ Visual acuity ↑ Perception of space ↑ Aesthetics ↓ Errors ↓ Eye fatigue
62	O	Daylight modeling	1. Proper amount of sunlight throughout the year.	↑ Alertness ↑ Circadian rhythm alignment ↑ Sleep quality ↑ Cognitive functions (learning) ↑ Mood
63	O	Daylighting fenestration	1. A proper window-wall ratio with a proper amount of heat and glare control. 2. High enough transmittance of glazing. 3. Uniformity in window transmittance.	↑ Visual acuity ↑ Perception of space ↑ Aesthetics ↓ Errors ↓ Eye fatigue
*Precondition/optimization. **From parts that are related to office lighting.				

WELL v2

For WELL Building Standard v2, the number of features has been reduced to eight, out of which two are preconditions and six are optimizations. Like in v1, each feature has parts, and parts have requirements. However, the point system is more flexible; the optimizations award a varying amount of point, depending on the parts. The features and their corresponding targets are summarized in Table 7 along with the ways through which they affect well-being. [73]

Table 7. Office-related light features and targets of WELL Building Standard v2 [73], and the ways how they influence well-being.

No	P/O*	Feature	Target**	Affects well-being by increasing ↑ / decreasing ↓
L01	P	Light exposure and education	1. Enough sunlight throughout the year, proximity to envelope glazing, high enough transmittance of glazing, a high enough window-wall ratio. 2. People are educated about the effects of lighting on health and well-being.	↑ Alertness ↑ Circadian rhythm alignment ↑ Sleep quality ↑ Cognitive functions (learning) ↑ Mood
L02	P	Visual lighting design	1. Proper illuminance level for different tasks and occupant ages.	↑ Visual acuity ↑ Perception of space ↓ Errors ↓ Eye fatigue
L03	O (3)	Circadian lighting design	1. High enough vertical illuminance at eye level for long enough.	↑ Alertness ↑ Circadian rhythm alignment ↑ Sleep quality

				↑ Cognitive functions (learning) ↑ Mood
L04	O (3)	Glare control	1. A system to prevent solar glare (without continuously blocking natural light), proper amount of sunlight throughout the year. 2. Luminaires emit light only above the horizontal plane, they have a proper UGR value, they have a high enough shielding angle for their luminance, their luminance level is low enough for each point of view.	↓ Eye fatigue ↓ Distraction
L05	O (3)	Enhanced daylight access	1. Proximity to envelope glazing or atria, high enough transmittance of glazing, a high enough window-wall ratio. 2. Proper amount of sunlight throughout the year. 3. Proper outside views for occupants.	↑ Alertness ↑ Circadian rhythm alignment ↑ Sleep quality ↑ Cognitive functions (learning) ↑ Mood ↑ Aesthetics
L06	O (1)	Visual balance	1. Low enough contrasts between visually adjacent surfaces and spaces, long enough transition time for significant changes in light levels, illuminance uniformity on work planes.	↑ Visual acuity ↑ Perception of space ↓ Fatigue ↓ Distraction
L07	O (2)	Electric light quality	1. Lighting has a high enough color rendering index. 2. Lighting has proper flicker and frequency properties.	↑ Perception of space ↑ Aesthetics ↓ Headache
L08	O (2)	Occupant control of lighting environments	1. Lighting is automated and tunable, occupants can adjust the lighting levels, color temperature and color of lighting. 2. Supplemental lighting can provide a high enough level of illuminance, it is free, it is available upon request in a reasonable time.	↑ Visual acuity ↑ Feeling of control ↑ Alertness ↑ Circadian rhythm alignment ↑ Sleep quality ↑ Cognitive functions (learning) ↑ Mood
*Precondition/optimization. Points awarded are in brackets. **From parts that are related to office lighting.				

There are some significant changes in v2 in comparison to the older version. New parts have been added, and others have been cut out. The changes are best elucidated in Table 8, where the requirements have been grouped into several lighting-related categories. The reason for the differences are discussed in chapter 4.

Table 8. Differences and similarities between WELL v1 and WELL v2, grouped into lighting-related categories.

Category	Included in WELL v1	Included in both	Included in WELL v2
Light levels	- Luminaire zoning - Automated solar dimming	- Illuminance level	- Consideration of different tasks and ages
Circadian lighting		- Circadian illuminance level	

Glare control	- Automated shading - Anti-glare attributes on computer screen	- Luminaire shielding angle - Luminance limits for viewing angles - Solar glare prevention	- Continuity of shading - Light emitted only above the horizontal plane - UGR values
Lighting control	- All lighting with occupancy sensors - All lighting with daylight sensors		- Widely tunable lighting - Allowing occupants to control lighting
Contrasts		- Luminance differences between surfaces	- Transition time in light level changes - Illuminance uniformity on work plane
Colors		- Color rendering index	
Windows	- Transmittance uniformity - Extra control for heat and glare for spaces with high window-wall ratio	- Distance to outside views - Window transmittance - Window-wall ratio	
Others	- Surface reflectances	- Yearly amount of sunlight	- Lighting flicker - Educating people about the effects of light

3. Case studies

Overview

This chapter covers in detail three studies made to examine the current state of lighting from the point of view of well-being. The case studies were done by performing lighting measurements and assessments in three offices with different features. It serves this thesis in two ways: it helps to identify common areas for improvement in office lighting for well-being and it gives tools to critically discuss lighting standards regarding well-being. Furthermore, although the case study is mostly qualitative, it may provide the reader benchmarks against which to compare other offices.

This chapter consists of three subchapters, each focusing on one office, which are called Office 1, Office 2 and Office 3. Each section follows the same pattern, which is described in Table 9.

Table 9. Outline pattern of the sections of chapter 3.

Chapter	Headline	Explanation
3.x.	Office --	Details of the building and the interior of the office.
3.x.1.	Motivation	Why this office was chosen for the study.
3.x.2.	Measurements and assessments	Conditions and methods of the measurement and assessment process.
3.x.3.	Meeting the standard	To what extent the office complies with WELL v1.
3.x.4.	Plan for changes	How the well-being in the office could be improved.

The measurements and assessments in the case studies are based on the lighting requirements of the WELL Building Standard v1. This standard was originally chosen, because it was the only standard focusing in human well-being, and its requirements are comprehensive and well defined. Features 62 and 63 of WELL v1 were not included in the studies, as they are related to the amount of sunlight of the geographical area and architectural features. The requirements of each part are presented in Table 10, by specifying the office area that the standard refers to, the specific measuring distance or angle and the goal value to pass the requirement.

Table 10. Details of the case studies' measurements and assessments based on the WELL standard [72].

<table>
<tr><th>Feat.</th><th>Part</th><th>Office area</th><th>Specifics</th><th>Goal</th></tr>
<tr><td>53-1</td><td>Visual acuity for focus</td><td>Workstations or desks</td><td>Horizontal plane at 0,76 m</td><td>Average over 215 lx. If ambient is below 300 lx, task light 300–500 lx.</td></tr>
<tr><td rowspan="4">53-2</td><td rowspan="4">Brightness management strategies</td><td>Main rooms and ancillary spaces</td><td></td><td>Difference in magnitude cannot exceed the factor of: 10</td></tr>
<tr><td>Task surfaces and immediately adjacent surfaces</td><td></td><td>Factor of 3</td></tr>
<tr><td>Task surfaces and remote, non-adjacent surfaces in the same room</td><td></td><td>Factor of 10</td></tr>
<tr><td>Two parts of the ceiling in the same room</td><td></td><td>Factor of 10</td></tr>
<tr><td rowspan="2">54-1</td><td rowspan="2">Melanopic light intensity for work areas</td><td>On at least 75% of workstations</td><td rowspan="2">Vertical plane forward at 1,2 m.</td><td>≥ 200 EML (equivalent melanopic lux) from 9 to 13 every day of the year.</td></tr>
<tr><td>All workstations</td><td>Electric lights: ≥ 150 EML.</td></tr>
</table>

55-1	Luminaire shielding	Regularly occupied spaces	At the shielding angle	If above 20 000 cd/m^2, angle should be 15°. If above 50 000 cd/m^2, angle should be 20°. If above 500 000 cd/m^2, angle should be 30°.
55-2	Glare minimization	Workstations, desks and other seating areas	At over 53°.	Under 8 000 cd/m^2.
56-1	View window shading	Regularly occupied spaces	Glazing under 2,1 m above the floor.	Window shading or blinds / external shading / variable opacity glazing with min 90% transmittance.
56-2	Daylight management	Regularly occupied spaces	Glazing over 2,1 m above the floor.	Window shading or blinds / external shading / interior light shelves / micro-mirror film / variable opacity glazing with min 90% transmittance.
57-1	Glare avoidance	Computer workstations	Within 4,5 m of view windows.	Computer screens can be oriented to 20° perpendicular to nearest window.
58-1	Color rendering index	All electric lights (except decorative fixtures, emergency lights and other special-purpose lighting)		R1–R8: at least 80. R9: at least 50.
59-1	Working and learning area surface reflectivity	Working area: Ceilings have…	≥ 80% of surface area.	Average reflectance of at least 80%.
		Vertical surfaces have…	≥ 50% of surface area.	Average reflectance of at least 70%.
		Furniture systems have…	≥ 50% of surface area.	Average reflectance of at least 50%.
60-1	Automated sunlight control	Windows larger than 0,55 m^2		Anti-glare shading devices triggered by daylight.
60-2	Responsive light control	Major workspace areas	All lighting except decorative fixtures.	Automatic dimming to 20% on inoccupancy. Daylight harvesting.
61-1	Lease depth	75 % of regularly occupied spaces		Within 7,5 m of view windows.
61-2	Window access	75 % of workstations		Within 7,5 m of an atrium or exterior view windows.
		95 % of workstations		Within 12,5 m of an atrium or exterior view windows.

Materials

The measurement equipment consisted of an illuminance meter (lux meter), a luminance meter, a laser rangefinder and a mobile phone working as a spirit level and an angle ruler. The lux meter was used to measure both illuminance and color rendering index. A tripod was used to stabilize the otherwise handheld devices. In addition, a piece of wood was cut in a 53° angle to be able to repeatedly and quickly achieve the desired angle for the measurement for feature 55-2. For easy documentation on the run, the floor plan of the office was printed on paper. The lux meter had memory capacity to store the illuminance and color rendering index measurements. Other measurement results were written down with pen and paper.

For the measurements at Office 2 and Office 3, the lux and luminance meters used at Office 1 were not available. This resulted in not being able to conduct all the measurements in a similar manner, which will be explained in detail later. Another type of a lux meter was used, which had no memory capacity, but it had the advantage of directly measuring the EML[3] (equivalent melanopic lux) value of light. For clarity, all the equipment for each office is shown in Table 11.

Table 11. Equipment used in the case studies' measurements.

Equipment for	Office 1	Office 2	Office 3
53-1	Illuminance (lux) meter 1	Illuminance (lux) meter 2	Illuminance (lux) meter 2
53-2	Luminance meter	-	-
54-1	Illuminance (lux) meter 1	Illuminance (lux) meter 2	Illuminance (lux) meter 2
55-1	Luminance meter Mobile phone	Mobile phone	Mobile phone
55-2	Luminance meter Piece of wood cut to 53° Laser rangefinder	-	-
58-1	Illuminance (lux) meter 1	Illuminance (lux) meter 2	Illuminance (lux) meter 2
59-1	Illuminance (lux) meter 1 Luminance meter	Illuminance (lux) meter 2	Illuminance (lux) meter 2
Documentation	Printed floor plan Pen Paper	Printed floor plan Pen Paper	Printed floor plan Pen Paper
Stabilization	Tripod	Tripod	Tripod

3.1. Office 1

Office 1 takes up most of the fourth floor of an office building located in Espoo. The office was built in 2001 and the lighting was renovated in 2016. The building is quite narrow with large windows, and other buildings do not cast shadows on the office. A sea view on one side of the building increases the light level at that end of the office.

Upon entrance, the office gives a rather bright impression. The interior decoration is mostly white or light colored, with a few colored pieces of furniture, such as the partitions between workstations and chairs. The windows have manual blinds, except for the sea side windows, which are shaded with an automatized curtain system. The HVAC piping in the ceiling is shielded, but not recessed, which results in a very uneven surface.

3.1.1. Motivation

The lighting in Office 1 is quite new and represents the latest LED technology from many different luminaire manufacturers. The installations have been designed to meet and exceed the requirements of the lighting standard *EN 12464-1 Light and lighting. Lighting of work places. Part 1: Indoor work*

[3] The EML value is calculated by matching the light spectrum to the human melanopic spectral efficiency function. [74]

places. The office is an interesting subject for the case study, as it allows to see how well modern lighting complies with the most recent well-being guidelines.

3.1.2. Measurements and assessments

Conditions

To get results at the worst possible lighting conditions, the measurements were conducted at night time in February. This way it could be seen if the lighting installations in the office provided good enough lighting even at the darkest times of the year. Measuring after office hours also allowed working without interruptions or disrupting other workers.

Process

The measurements that required the lux meter and the tripod were conducted first: 53-1, 54-1 and 58-1. In total 23 measurement points were chosen evenly around the office area, both in working areas and meeting rooms. The motorized tables at the workstations were set to a height of 0,76 m in advance to be able to easily conduct measurement 53-1. The tripod was set to 1,2 m for 54-1. Keyboards on workstations were moved slightly away. For 58-1, no setup is needed, as the lux meter would record the color rendering indices simultaneously with illuminance values.

A repeatable cycle was established; (1) move to a measurement point, (2) measure the horizontal illuminance at two points on the desk, roughly at the two ends of a keyboard, (3) put the tripod against the front of the desk, (4) attach the lux meter to the tripod and measure the vertical illuminance. On step (2), the points were chosen to be under both ends of a supposed keyboard position, or equivalent spots on a meeting room. Furthermore, on step (2) it was important to not block the light entering the lux meter.

Next was 59-1, surface reflectance, for which both illuminance on a spot on a surface and the luminance of that same spot had to be measured. A total of 25 measurement points of different surfaces were chosen in ceilings, vertical surfaces and furniture systems. For illuminance measurement, no easy way was found to attach the lux meter on surfaces. Hence, for walls, the meter had to be held in hand while leaning flat against the wall. However, for ceilings, it was impossible to measure without partly blocking light from below. The luminance measurement was more straightforward, it simply required pointing the luminance meter at a desired point from far enough to not interfere with the light.

Measurement 55-1, to determine shielding angles of luminaires, required mapping all the different luminaires in the office, resulting in a total of 15. The measurement was conducted by attaching the luminance meter on the tripod, targeting it towards the ceiling and laying the mobile phone on top of the meter to determine the angle. Each luminaire was first measured from a 15° angle, and if the luminance had exceeded 20 000 cd/m^2 the angle would have been increased to 20°. Again, if the luminance had exceeded 50 000 cd/m^2, the angle would have been increased to 30°. Each luminaire was measured from three different points, because even slight deviations from the brightest part, the middle of the light source, would already result in a much lower luminance.

For 55-2, the piece of wood with a 53° angle was attached to the tripod which was set at the height of 1,2 m to represent seated eye height. Because of the symmetry of the office tables in relation to the overhead luminaires, only 6 measurement points were chosen. The tripod was put against the front of each desk, and the laser rangefinder was put against the piece of wood, then pointing at a 53° towards the ceiling. If the overhead luminaire had then been situated above the laser point, the luminance meter would have been used to measure the luminaire luminance by laying the meter against the piece of wood.

The final measurement was 53-2, comparing the brightness of different visually adjacent surfaces. Eleven measurement points were chosen by looking for subjectively high brightness differences around the office. Then the luminance values of these surfaces were measured by pointing the luminance meter at the high and the low brightness surface.

3.1.3. Meeting the standard

While the initial general impression of Office 1 in terms of lighting is very good, the office does not pass all the strict requirements of the WELL Building Standard v1. The measurement and assessment results are presented in Table 12, and they are compared with the WELL v1 requirements. More detailed results of each measurement point can be viewed in Appendix A.

The office is very bright, and the illuminance values far exceed the visual threshold (53-1). The physiological EML requirement (54-1) is barely not met in a few particular spots, but if the measurements were done in daytime, the value would certainly be met. All the different luminaires pass the shielding requirements for their luminance values (55-1). However, their positioning could be better, as many bright luminaires are located within the forbidden angle in front of the workstations (55-2). Another issue is their color rendering capability, which is enough for the traditional Ra value, but significantly fails at R9 (58-1).

There are several different surfaces in the office that were studied. In terms of reflectivity, they pass the requirements, except for the workstation partitions (59-1), which take up most of the views when seated on a workstation. Furthermore, their contrasts are too high, as the white desk and the colored partitions have very different luminance values (53-2). The luminance of the ceiling is also too uneven. However, the requirement for small luminance differences between spaces is achieved, as there are no dark ancillary spaces.

Because the building is only 15,6 meters wide, and there are windows on all outside walls, the requirements for distance from windows are easily passed (61-1, 61-2). Glare from sunlight is mitigated with manual blinds on all windows (56-1, 56-2). There is also a sensor-triggered curtain on the sea side windows, where the sun glares the most, but it is not enough to fulfill the requirements (60-1). Photosensors also dim down the lights under daylight and PIR movement sensors dim them when the areas are unoccupied (60-2). The computer screens in the office can be turned to avoid glare (57-1).

Table 12. Results of the measurements at Office 1 compared to WELL v1.

Feat.	Part	Goal	Measurement/assessment results	Reaching the goal
53-1	Visual acuity for focus	Average over 215 lx. If ambient is below 300 lx, task light 300–500 lx.	The average illuminance was 895 lx, and the lowest value was 563 lx.	Pass
53-2	Brightness management strategies	Difference in magnitude cannot exceed the factor of: 10	There are no dark ancillary spaces in the office.	Pass
		Factor of 3	The luminance difference between desks and workstation partitions is too high.	Fail
		Factor of 10	The luminance difference between desks and workstation partitions is too high.	Fail

		Factor of 10	The ceiling luminance above the luminaires with uplighting varied from 30 to 500 cd/m^2.	Fail
54-1	Melanopic light intensity for work areas	≥ 200 EML from 9 to 13 every day of the year.	Average EML: 331. 8% of the measurements had an EML value under 150, the lowest being 129.	Pass
		Electric lights: ≥ 150 EML.		Fail
55-1	Luminaire shielding	If above 20 000 cd/m^2, angle should be at least 15°.	11 out of 16 different luminaires had a measured luminance below 20 000 cd/m^2 and their average value was 4 700 cd/m^2. The shielding angles for the brighter luminaires were within the limits.	Pass
		If above 50 000 cd/m^2, angle should be at least 20°.		Pass
		If above 500 000 cd/m^2, angle should be at least 30°.		Pass
55-2	Glare minimization	Under 8 000 cd/m^2.	89% of the measured luminances were over 8 000 cd/m^2 and 84% of those were at an angle between 53° and 90°.	Fail
56-1	View Window Shading	Shading.	Blinds on windows.	Pass
56-2	Daylight Management	Shading.	Blinds on windows.	Pass
57-1	Glare Avoidance	Computer screens can be oriented to 20° perpendicular to nearest window.	The computer screens can be turned.	Pass
58-1	Color rendering index	R1–R8 (Ra): at least 80. R9: at least 50.	The average Ra was 84, but the average R9 was 18.	Fail
59-1	Working and learning area surface reflectivity	80% of ceiling area: average reflectance of at least 80%.	Subjective evaluation: the ceiling varied very much, but most of the elements had a measured reflectance of over 80%.	Likely
		50% of vertical surface area: average reflectance of at least 70%.	Subjective evaluation: most of the elements had a measured reflectance of over 70%.	Likely
		50% of furniture systems area: average reflectance of at least 50%.	Subjective evaluation: white desks pass, but workstation partitions do not. When seated, the partitions take most of the view.	Unlikely
60-1	Automated Sunlight Control	Anti-glare shading devices triggered by daylight.	Automated curtains on the side of the building where the sun shines the strongest.	Fail
60-2	Responsive Light Control	Automatic dimming to 20% on unoccupancy.	PIR sensors dim the lighting.	Pass
		Daylight harvesting.	Photosensors dim the lighting.	Pass
61-1	Lease Depth	Spaces within 7,5 m of view windows.	The building is only 15,6 m wide.	Pass
61-2	Window Access	Workstations within 7,5 m of an atrium or exterior view windows.	The building is only 15,6 m wide.	Pass
		Workstations within 12,5 m of an atrium or exterior view windows.	The building is only 15,6 m wide.	Pass

3.1.4. Plan for changes

As the previous subchapter showed, Office 1 does not comply with the WELL Building Standard v1 as is. What kind of changes could be made in the office to meet the requirements, and how easily could they be implemented?

Probably the most straightforward changes consider the workstation partitions in 53-2, which have too low a luminance in comparison to the white desk. Their reflectance is also too low for 59-1. Replacing the dark colored partitions with ones with lighter coloring would solve the problem. For the luminance unevenness in the ceiling above the workstations, lowering the luminaires could help. As can be seen from Equations 1–3 below, as the distance between the light source and the ceiling increases, the luminous intensity decreases in the square of the distance. This, in turn, decreases the illuminance of the surface, which is directly proportional to its luminance.

Illuminance produced by a point source: [75]

$$E = \frac{I}{r^2} \cdot sr \tag{1}$$

where

E is the illuminance of the surface
I is the luminous intensity
r is the distance between the light source and the surface
sr is the steradian unit.

When the intensity is a constant, increasing the distance causes illuminance to decrease.
The luminance of a diffuse surface is: [75]

$$L = \frac{\rho E}{\pi \cdot sr} \tag{2}$$

where

L is the luminance of the surface
ρ is the reflectance of the surface
sr is the steradian unit.

Thus, increasing the distance decreases the luminance. (3)

$$L = \frac{\rho I \cdot sr}{\pi \cdot r^2 \cdot sr} = \frac{\rho I}{\pi \cdot r^2}$$

Lowering the luminaires would also help in solving glare for 55-2 as well. The requirement of 55-2 is to not have a luminance over 8 000 cd/m^2 above an angle of 53° from the point of view. The workstation luminaires could be lowered right below the 53° view angle, so the luminance of over 8 000 cd/m^2 would no longer matter, as can be seen from Figure 5. This could be achieved relatively easily, as the luminaires are suspended with an adjustable metal wire. While this would slightly decrease the vertical EML for 54-1, the illuminance level would most likely still exceed the requirements.

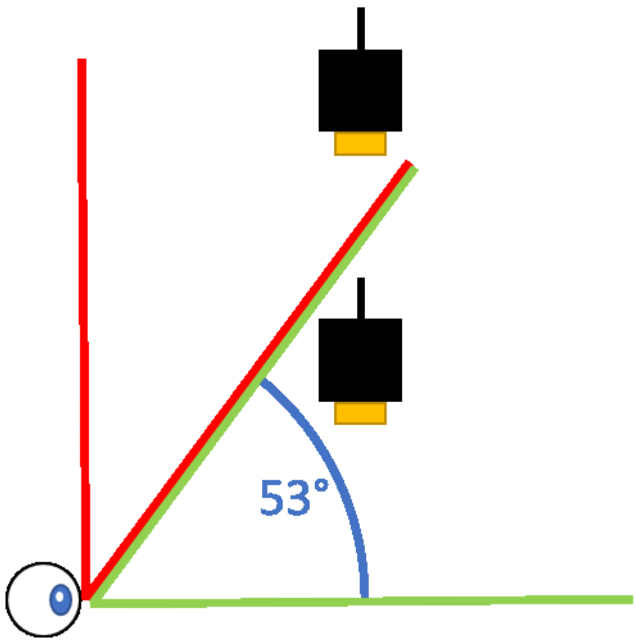

Figure 5. Illustrative drawing of the viewing angle limitations of the WELL Building Standard v1 55-2.

60-1 could be achieved by installing automatic curtains on the rest of the windows, but it is unlikely that the tenants would want that, as there already are manual blinds on all windows. For the color rendering index in 58-1 there is no simple fix. The traditionally required Ra value is fine, but the level of red-rendering that R9 expresses, is not even nearly achieved. To meet the standard, almost all the luminaires would have to be replaced, which is not a realistic option for an office with functional and fairly new lighting.

3.2. Office 2

Office 2 is located in the floor right below Office 1 and therefore the environmental attributes of the office are virtually identical (see 3.1.). The office extends to the whole floor (unlike Office 1) and the lighting installations are older than upstairs.

The first impression of Office 2 is cozy, as a result of the colorful inside decorations. However, the rows of identical fluorescent luminaires do not seem evenly lit. The fitted carpets are light green, yellow and grey, and similar colors have been used in textiles around the space. The furniture is mostly black, with black workstation partitions. There are also several plants scattered throughout the office. The roof is the same as in Office 1, very uneven because of ventilation elements, but with less lighting fixtures. The windows have manual blinds.

3.2.1. Motivation

Office 2 was chosen because it allows the comparison of two very similar offices in terms of environmental attributes and floor plan, but with different lighting and decoration. The lighting of Office 2 is quite homogenous, and the lighting control is more limited. When compared with Office 1, the study provides a great example of what can be achieved with different lighting systems and interior design when the layout is the same. The easy accessibility also contributed to the decision of including the office in the study.

3.2.2. Measurements and assessments

Conditions

Office 2 could not be accessed at night time, so the measurements were conducted at 9.00 in the morning. Because the measurements took place on April, there was already natural light present at that time of the day. Therefore, window shades were closed for the duration of the measurement process in each area. During the measurements, people working in the office had to be taken into consideration.

Because with the equipment available at the time it was not possible to measure the luminance, all the same measurements as at Office 1 could not be conducted. Thus, 55-2 had to be left out and 53-2 had to be subjectively evaluated. 59-1 had to be measured through illuminance values only. 55-1 had also to be measured differently, as is explained later.

Process

As the layouts of Office 2 and Office 1 were similar, whenever possible, the measurement points were chosen to be the same ones as in Office 1. However, sometimes there would be people working on a certain point, so an adjacent one was picked. While the office extended to the whole floor, only the part that was directly under Office 1 was measured.

The measurements for 53-1, 54-1 and 58-1 were conducted the same way as in the floor above, except for not setting the height of the motorized tables, because of people working on them. In total, measurements were made from 16 points.

The surface reflectance for 59-1 was measured in two parts. First, the illuminance was measured from a spot on a surface. Then, a second measurement was taken from the light reflected from the surface. This was done by holding the lux meter towards the surface from a roughly 50 cm distance. It was, of course, impossible to do without partly blocking the light on the surface.

The shielding angles in 55-1 were measured by using the mobile phone to determine angles. There were 3 different luminaires in the office, but one type of them was diffuse and the other had a microprism shield, which scatters the light. Therefore, those two did not require measurements, but the third one did. The light source in the luminaire was viewed along the side of the phone, and the measurer slightly moved backwards and tilted the phone until the light source was behind the shield. Then the angle was written down. Because the angle was over 30°, no luminance measurement was needed.

3.2.2. Meeting the standard

Office 2 did not pass all the WELL v1 requirements. The measurement results and their comparison to the requirements can be seen in Table 13. A more detailed view of the results of each measurement point is presented in Appendix B.

The horizontal lighting level of the office is not high enough (53-1). While the average illuminance is almost 600 luxes, the value varies significantly from one place to another. In four out of 16 measurements, the level is below 300 lx, while in two it is around 1200 lx. The vertical illuminance for the physiological effects of light (54-1) is also too low, as over half of the measurements resulted in a value below the electrical light limit of 150 EML. All of the three luminaire models pass the shielding requirements (55-1) and the color rendering for Ra, but not for R9 (58-1).

Based on the subjective evaluation of the space, it seems probable that in the brightness management (53-2) two out of four requirements are fulfilled. There are no dark ancillary spaces. The ceiling does not seem to have great luminance differences, as there is no uplighting. The problem is the black furniture, which creates a big contrast against the light surfaces. In addition, the dark furniture and the colored walls, floors and decorations have too low a reflectance (59-1).

Glare on workstations is avoided by having adjustable computer screens (57-1) and window blinds (56-1, 56-2) without automation (60-1). There are no occupancy sensors and the luminaires are equipped with daylight sensors, which do not seem to work (60-2). The 15,6-m width of the building ensures that enough spaces and workstations are close to windows (61-1, 61-2).

Table 13. Results of the measurements at Office 2 compared to WELL v1.

Feat.	Part	Goal	Measurement/assessment results	Reaching the goal
53-1	Visual acuity for focus	Average over 215 lx. If ambient is below 300 lx, task light 300–500 lx.	The average illuminance was 579 lx, and the lowest value was 211 lx.	Fail
53-2	Brightness management strategies	Difference in magnitude cannot exceed the factor of: 10	There are no dark ancillary spaces in the office.	Pass
		Factor of 3	Subjective evaluation: the luminance difference between black desks and light floor seems too high.	Unlikely
		Factor of 10	Subjective evaluation: the luminance difference between black workstation partitions and white walls seems too high.	Unlikely
		Factor of 10	Subjective evaluation: the ceiling seems uniform.	Likely
54-1	Melanopic light intensity for work areas	≥ 200 EML from 9 to 13 every day of the year.	Average EML: 184. 56% of the measurements had an EML value under 150, the lowest being 83.	Fail
		Electric lights: ≥ 150 EML.		Fail
55-1	Luminaire shielding	If above 20 000 cd/m^2, angle should be at least 15°.	The shielding angle of the single luminaire type with a normal shield was over 30°.	Pass
		If above 50 000 cd/m^2, angle should be at least 20°.		Pass
		If above 500 000 cd/m^2, angle should be at least 30°.		Pass
55-2	Glare minimization	Under 8 000 cd/m^2.	N/A	N/A
56-1	View Window Shading	Shading.	Blinds on windows.	Pass
56-2	Daylight Management	Shading.	Blinds on windows.	Pass
57-1	Glare Avoidance	Computer screens can be oriented to 20° perpendicular to nearest window.	The computer screens can be turned.	Pass
58-1	Color rendering index	R1–R8 (Ra): at least 80. R9: at least 50.	The average Ra was 83, but the average R9 was 16.	Fail
59-1	Working and learning area	80% of ceiling area: average reflectance of at least 80%.	Subjective evaluation: the ceiling varied very much, but most of the	Likely

	surface reflectivity		elements had a measured reflectance of over 80%.	
		50% of vertical surface area: average reflectance of at least 70%.	White wall reflectance was 71%. Subjective evaluation: they cover most of the vertical surfaces.	Likely
		50% of furniture systems area: average reflectance of at least 50%.	Subjective evaluation: black desks and workstation partitions are too dark.	Unlikely
60-1	Automated Sunlight Control	Anti-glare shading devices triggered by daylight.	No automation on curtains.	Fail
60-2	Responsive Light Control	Automatic dimming to 20% on inoccupancy.	No PIR sensors.	Fail
		Daylight harvesting.	Photosensors dim the lighting.	Fail
61-1	Lease Depth	Spaces within 7,5 m of view windows.	The building is only 15,6 m wide.	Pass
61-2	Window Access	Workstations within 7,5 m of an atrium or exterior view windows.	The building is only 15,6 m wide.	Pass
		Workstations within 12,5 m of an atrium or exterior view windows.	The building is only 15,6 m wide.	Pass

3.2.3. Plan for changes

For Office 2 to meet the requirements of the WELL Building Standard v1, changes would have to be made. Before estimating the feasibility of each change, the current luminaires should be examined better. As could be noticed upon entrance, the luminaires are unevenly and some of them very dimly lit, which could be related to the sensors mounted in each luminaire. While the office users could not tell their purpose, they probably are light sensors to tune the lighting according to the amount of daylight. For some reason, they have ceased to work correctly, and calibrating or completely disabling them would likely increase the lighting levels for 53-1 and 54-1. It is hard to determine the cost of calibration, but the disabling could be done by simply covering the sensors, with tape, for instance. This would stop the daylight harvesting functionality, but nonetheless it does not seem to work correctly.

Without further knowledge of the light sensor issue, probably the easiest changes would consider the interior decorations. However, quite many materials and colors would have to be altered, which would raise costs. For the furniture, switching the desks and partitions for ones with lighter colors would help not only to moderate the contrast differences for 53-2, but to increase the amount of light for the users' eyes for 54-1. Many walls and surfaces could also have their color changed to something lighter for 59-1.

While the changes on surfaces would increase the illuminance of the space for 53-1 and 54-1, it would probably not be enough. It is possible that even calibrating or disabling the light sensors would not suffice. Probably the whole lighting should be renovated to meet the lux and EML requirements. That would also solve 58-1, for which the only option is to implement new lighting with a high enough R9 value. The new system could use both daylight and presence sensors to fulfill 60-2. Given that the current lighting installation is quite old, a complete renovation could be a reasonable option. By installing automatic blinds 60-1 could be achieved, but the tenants probably would not bother, as there already are manual blinds everywhere.

3.3. Office 3

Office 3 is in the sixth and seventh floor of an office building located in Helsinki. It was finished in 2016, but an extension is being built, which is estimated to be finished in 2019. There are no other buildings nearby that would cast shadows on the tall building, but it is T-shaped, which slightly darkens the inner corners. After the extension is ready, the building will be H-shaped, which could leave some windows in shadow.

The interior is formal, with mostly black and white furniture, and dark, thin curtains. The windows do not have blinds. The ceiling is even and white, as are the walls, but the carpet is quite dark. There are some plants for decoration.

3.3.1. Motivation

Office 3, being brand new, brings another dimension of comparison to this thesis. One could assume that well-being aspects would more probably have been taken into account in a newer building than in the older ones. Of course, this is only a single case, which does not prove this hypothesis. Moreover, the building was awarded with a platinum level LEED certificate. While it is not directly related to well-being, it implies special considerations at the design phase. These two facts make Office 3 an interesting addition to this thesis.

3.3.2. Measurements and assessments

Conditions

For scheduling reasons, Office 3 had to be accessed during daytime, starting from 14.00 in the afternoon. Therefore, natural light was present during the measurements, and it was not fully cancelled by the curtains shading the large windows. Furthermore, it was not possible to close the curtains at every point in the area without disrupting office workers. Thus, some of the curtains were left open and others closed.

Process

The sixth and the seventh floor of the building had an almost identical layout, so the measurements were mainly taken in the seventh one. 12 measurement points were in the seventh floor, and 1 in the sixth.

All the measurements were conducted the same way as in Office 2. Again, 55-2 had to be omitted and 53-2, 59-1 and 55-1 changed. In the case of 55-1, the angles of the office overhead luminaires were over 30°, and other luminaires were diffuse or had a microprism shield.

3.3.3. Meeting the standard

Office 3 does not fully comply with the WELL Building Standard v1. The measurement results are presented in Table 14, where they are compared to the requirements of WELL v1. Appendix C shows a more detailed view to the results of each measurement point.

First, it must be re-emphasized that the office was partially lit by daylight, which most probably affected the results. Despite this, the visual acuity demands (53-1) would probably still be fulfilled, as the average illuminance was threefold to the requirements. Moreover, the EML value being almost double to the requirements, the melanopic (54-1) threshold for electric lights would also most likely be passed. Naturally, for the EML threshold that considers daylight, present daylight did not matter. Once again, the R9 color rendering index is too low (58-1), and the fact that it is quite much higher than in the previous offices, can most probably be explained by the daylight. Office 3 had only three different luminaire models, which all passed the shielding requirements (55-1).

For the brightness management (53-2), according to the subjective evaluation, two requirements are likely to be achieved, and two are unlikely. The ceiling is not only uniform, but seems well lit. Again, there are no dark ancillary spaces, but the furniture causes large contrast differences. The workstation partitions and shelves also seem to have too low a reflectance value (59-1), but the ceiling and vertical surfaces seem to pass the requirements.

The office is equipped with daylight and presence sensors to dim the lights down when not needed (60-2). There are no automated anti-glare systems (60-1), but manual curtains (56-1, 56-2). Computer screens can be turned to further avoid glare (57-1). The building is big and wide, but the workstations have been placed near the windows, mostly at a distance under 7,5 m (61-1, 61-2).

Table 14. Results of the measurements at Office 3 compared to WELL v1.

Feat.	Part	Goal	Measurement/assessment results	Reaching the goal
53-1	Visual acuity for focus	Average over 215 lx. If ambient is below 300 lx, task light 300–500 lx.	The average illuminance was 820 lx, and the lowest value was 632 lx.	Pass
53-2	Brightness management strategies	Difference in magnitude cannot exceed the factor of: 10	There are no dark ancillary spaces in the office.	Pass
		Factor of 3	Subjective evaluation: the luminance difference between white desks and dark workstation partitions seems too high.	Unlikely
		Factor of 10	Subjective evaluation: the luminance difference between dark workstation partitions and white walls seems too high.	Unlikely
		Factor of 10	Subjective evaluation: the ceiling seems uniform.	Likely
54-1	Melanopic light intensity for work areas	≥ 200 EML from 9 to 13 every day of the year.	Average EML: 389. The lowest value was 221.	Pass
		Electric lights: ≥ 150 EML.		Likely
55-1	Luminaire shielding	If above 20 000 cd/m^2, angle should be at least 15°. If above 50 000 cd/m^2, angle should be at least 20°. If above 500 000 cd/m^2, angle should be at least 30°.	The shielding angle of the single luminaire type with a normal shield was over 30°.	Pass
				Pass
				Pass
55-2	Glare minimization	Under 8 000 cd/m^2.	N/A	N/A
56-1	View Window Shading	Shading.	Curtains on windows.	Pass
56-2	Daylight Management	Shading.	Curtains on windows.	Pass

57-1	Glare Avoidance	Computer screens can be oriented to 20° perpendicular to nearest window.	The computer screens can be turned.	Pass
58-1	Color rendering index	R1–R8 (Ra): at least 80. R9: at least 50.	The average Ra was 85, but the average R9 was 30.	Fail
59-1	Working and learning area surface reflectivity	80% of ceiling area: average reflectance of at least 80%.	Subjective evaluation: white metal panels cover most of the ceiling.	Likely
		50% of vertical surface area: average reflectance of at least 70%.	White wall reflectance was 80%. Subjective evaluation: they cover most of the vertical surfaces.	Likely
		50% of furniture systems area: average reflectance of at least 50%.	Subjective evaluation: white desks pass, but workstation partitions and shelves do not. The furniture that does not pass has a bigger area.	Unlikely
60-1	Automated Sunlight Control	Anti-glare shading devices triggered by daylight.	No automation on curtains.	Fail
60-2	Responsive Light Control	Automatic dimming to 20% on inoccupancy.	PIR sensors dim the lighting.	Pass
		Daylight harvesting.	Photosensors dim the lighting.	Pass
61-1	Lease Depth	Spaces within 7,5 m of view windows.	Yes.	Pass
61-2	Window Access	Workstations within 7,5 m of an atrium or exterior view windows.	Yes.	Pass
		Workstations within 12,5 m of an atrium or exterior view windows.	Yes.	Pass

3.2.4. Plan for changes

While making changes in a brand-new office would probably not be easily approved, Office 3 would have to go through some changes in order to comply with the WELL Building Standard v1. Once again, the easiest necessary changes would probably be related to the interior decoration. However, just replacing the dark workstation partitions with lighter ones would suffice to achieve 53-2. Along with this, the black shelves should be lighter colored for 59-1.

Automatic blinds would be a fix for 60-1, but it is unlikely for the tenants to want that, as there already are curtains in the windows around the building. The only lighting-related change would consider 58-1, but again, changing all the luminaires is not a realistic option.

4. Discussion

This chapter attempts to answer the research question that was asked in the introduction: how to create an office environment that increases well-being? First it is discussed how the current rulebooks, standards, should be improved to match the level of scientific knowledge and technology of today. Then the results of the case studies are analyzed together with the standards to extract the most useful approaches for improving well-being through light. These approaches are then composed to form a guide to help in implementing suitable solutions for well-being in offices. Finally, recommendations are given for possible further research on the subjects covered in this thesis.

4.1. Improvements in office building standards for better well-being

As was covered in subchapter 2.3., lighting standards guide lighting design. They usually provide peer reviewed information and requirements for design, and thus also give designers a way to add credibility to their work. However, it is important to not trust them blindly, but to understand their limitations, to ensure best possible design.

This subchapter discusses the shortcomings of standards and suggests improvements, first for de jure standards and then for de facto standards. The differences between the standards addressed in this thesis are summarized in Table 36 in Appendix D.

Shortcomings of de jure standards and suggestions for improvement

The most recent and well-known de jure standard for lighting in office buildings is *EN 12464-1:2011 Light and lighting. Lighting of work places. Part 1: Indoor work places*. It includes a wide range of lighting design criteria to optimize visual performance, safety and visual comfort in many different environments. However, some of the physiological and psychological effects presented in subchapter 2.2.2 are omitted. Circadian rhythm is mentioned, but there are no requirements based on it, such as for the quantity or spectrum of light entering the eye at a certain time of the day. The standard should demand a minimum amount of vertical lighting at the eye level on the region of the peak of physiological response. Furthermore, while it is stated that illuminance should be increased for people whose visual capacity is below normal, the fact that the pupil transmittance is reduced with age is not taken into account. After all, the hindrance affects people of working age.

Another topic that is not covered sufficiently is lighting control, which is brought up only for energy savings, but not addressed from the point of view of well-being. Control systems can be used to tune the light intensity and spectrum of office lighting throughout the day to increase alertness when most needed, such as on dark early winter mornings or after lunch. Individual lighting control could help those suffering from sSAD or other types of depression by offering more light than usual. The standard should also mention the sense of autonomy that individual controls provide for people. Moreover, it could be useful to introduce information about tuning the light for different tasks depending on what kind of behavior is needed, such as collaboration or self-regulation. Now the standard gives threshold values for many variables for several different tasks but considers them only from the visual point of view.

An updated version of indoor lighting standards or a completely new standard is needed relatively fast for two reasons. First, there is an extensive amount of research about the physiological and psychological effects of light and lighting, as was elaborated in subchapter 2.2.2. Many of these studies have been made after 2011, which is the year when the newest version of the CEN standard was published. Even if back then there was some uncertainty about the plausibility of the results so far, now the information is boldly presented in one medium or another.

This leads to the second reason to pressure the publication of a new de jure standard; the notion of human centric lighting is spreading as a part of the well-being trend. If there is no legitimate source of information, other media is used. While there are many credible sources, some media may interpret scientific studies inaccurately, or cherry pick facts out of context. The gap is already being filled by a de facto standard, WELL Building Standard, which is discussed down below.

Another important, but not as urgent reason to push the de jure standardization organizations are smart systems and artificial intelligence. The technology has taken a great leap since 2011, and both their potential and possible problems in lighting should be addressed. Of course, the fact that the technologies develop very fast makes printed data expire quickly. Moreover, AI may be more thoroughly covered in other than lighting standards, but some lighting-related guidance on future systems should be given in a de jure lighting standard.

Perhaps the future standards currently being developed answer to these problems. Most promising for the physiological and psychological effects of light is *ISO/WD TR 21783 Light and lighting - Integrative lighting - Non-visual effects*. It is not certain if the standard will include control aspects, but maybe they will be addressed in *CEN/TS 17165:2018 Light and lighting - Lighting system design process*, which will most likely be published in the near future. Neither is it quite clear what the revised version of *EN 12464-1*, forecasted to be published in 2020 will include.

Shortcomings of de facto standards and suggestions for improvement

The three popular de facto standards introduced in this thesis, BREEAM, LEED and WELL, are all created by certification bodies. Therefore, it is hard to evaluate their impact in lighting design; will a designer follow them because of good lighting advice or just because the certificate is sought? These do not necessarily contradict each other, but de jure standards may offer more credibility. The certifiers may be seen as having a conflict of interest, as they charge money for the certification of their own standards. That is why it is important for the certifiers to be clear about what their requirements are based on and provide enough reliable sources to increase credence.

On the other hand, the laws of a competitive market may pressure the certifiers to aim for quality. If they are not credible, another standard may supersede them in the eyes of potential customers. They must also look for balance and update their standards accordingly, as requirements too strict to achieve would hinder interest. At the same time, they must follow the cutting edge of technology to remain modern and attractive. This, again, contradicts quality, as it may be hard to look at new research critically and objectively.

Of the three standards, BREEAM and LEED are competing each other, whereas WELL is filling the gap in the well-being market. While BREEAM and LEED have included some well-being aspects in their lighting requirements, they concentrate on environmental sustainability. Still, as they already include comfort aspects, they may as well consider mentioning non-visual effects of light in their next versions.

The position of WELL may seem good, as it is the first building certificate focusing solely on well-being. However, as in any business, it may be hard to set the bar. The facts that WELL v2 is piloting only four years after v1 and that the differences between their lighting requirements are quite significant, could suggest that the first version did not take off as planned. Because v2 is still a pilot, it is hard to tell if it will annul v1 or if some requirements of v1 will still make it to the launch of v2.

Some further standpoints on the evolution from v1 to v2 are included on the analysis of the case studies in the next subchapter.

In its current form, v2 lacks only one aspect of well-being from v1 which should be included, namely, the requirement for minimum surface reflectance values. Besides increasing the general illuminance of the space, surface reflectances contribute to the amount of vertical lighting, which has circadian effects. In comparison to *EN 12464-1:2011*, WELL is further on the right track with the circadian lighting, but WELL does not either take the timing of the light into consideration. Lighting control is addressed in WELL, but supporting circadian effects through control is not. These should be included in WELL for the same reasons as for *EN 12464-1:2011* described above.

A quite remarkable improvement from v1 to v2 is that v2 does not treat all the requirements as equal. Of course, v1 also has preconditions and optimizations, but all of them award the same amount of points. This puts more emphasis on gaining points, rather than striving for well-being. While it is hard to put the well-being effects in order, by awarding a varying amount of points v2 at least attempts to adduce that each effect has an impact of different magnitude.

As v2 was introduced recently, it is not likely that WELL will be updated in a while. Perhaps the next iteration will consider the missing issues, and given the speed of de jure standards, maybe in the future WELL will be a pioneer on standardization of smart lighting systems for well-being.

4.2. Renovations in offices to enhance well-being with light

The WELL Building Standard v1 was used as the background for the case studies to find out what kind of changes should be made in the lighting of an office to achieve well-being. WELL v1 was chosen, because it seemed to be a good basis to assess well-being in different office environments. However, the introduction of v2 undermined this basis, because many requirements were discontinued or changed. This slightly augmented the focus of this thesis from just using v1 for measurements to also analyzing its credibility.

Yet, the measurements and assessments provided a practical point of view to why a certain limit or other requirement was or was not reached. This subchapter first analyzes the results of the measurements made for the case studies in chapter 3, and then introduces a guide for renovating office lighting to improve well-being.

Analysis of the case studies

Comparing the results of the measurements and assessments of the case studies in chapter 3 leads to some deductions that help in forming the guide. The overall results of the three offices is shown in Table 15. Office 3 passed the most requirements, followed by Office 1 and finally Office 2. Of course, all the features are not equally easy to fulfill, and the impact on well-being varies.

Table 15. Overview of the case studies' results.

Feat.	Part	Office 1	Office 2	Office 3
53-1	Visual acuity for focus	Pass	Fail	Pass
53-2	Brightness management strategies	Fail	Likely	Likely
54-1	Melanopic light intensity for work areas	Pass	Fail	Pass
55-1	Luminaire shielding	Pass	Pass	Pass
55-2	Glare minimization	Fail	N/A	N/A
56-1	View Window Shading	Pass	Pass	Pass
56-2	Daylight Management	Pass	Pass	Pass

57-1	Glare Avoidance	Pass	Pass	Pass
58-1	Color rendering index	Fail	Fail	Fail
59-1	Working and learning area surface reflectivity	Unlikely	Unlikely	Unlikely
60-1	Automated Sunlight Control	Fail	Fail	Fail
60-2	Responsive Light Control	Pass	Fail	Pass
61-1	Lease Depth	Pass	Pass	Pass
61-2	Window Access	Pass	Pass	Pass
	Total passes and likely-to-passes:	9	7	10

There are six features that all the three offices passed:

- Window shading (56-1, 56-2) is quite naturally taken care of in all of them, probably because the consequence, solar glare, is obvious.
- Proximity to windows (61-1, 61-2) is the result of both architectural and furnishing decisions, which are most likely made because of views and daylight being generally seen as positive.
- While in the three offices adjustable computer screens were used (57-1), it is not self-evident for any given office to have them, as there are also fixed monitors in the market.
- Luminaire shielding angles seem to follow the same limits (55-1), as the results of all the various luminaires in Office 1 indicate. This is probably due to a wide consensus in the best practices of designing anti-glare luminaires. Furthermore, the WELL v1 limits are the same as in *EN 12464-1:2001*, which supports this explanation.

Three features could not be passed by any of the offices:

- Office 1 is the only one to embed automatic sunlight shading (60-1), but only on one wall, which is not enough to strictly comply. The fact that WELL v2 awards points from either automatic or manual shading suggests that this requirement has been found too strict.
- Probably the same applies to the color rendering index requirement for R9 (58-1), which has been softened for v2. The results are in line with this, as of all the measurements under various luminaires, only two give a result that complies with v1. This could indicate that currently there is no demand for high R9 and no pressure for the manufacturers to push such luminaires to the market.
- Low reflectance (59-1) was a common problem for furniture, but not for the ceiling and vertical surfaces, which were a likely pass for the three offices. Once again, this is a feature that was discontinued for v2, which together with the results suggests that the v1 requirement is too strict. However, as was mentioned before, reflectance has an effect on both the overall and circadian illuminance, and therefore it is important.

The last five features are the ones that had varying measurement results between offices:

- A separate case is the angular requirement for luminaire glare (55-2) measurement, which was conducted only in Office 1, so there is nowhere to compare the results to. This feature was altered and made optional for v2. While it can only be speculated, one reason for this could be in the difficulties on measurement, as luminance meters are rather expensive. The only other feature that requires luminance data is 55-1, which can in many cases be verified without a luminance meter, as was shown by the case studies.

- The results for the illuminance and EML (53-1, 54-1) would seem to suggest that with a high enough horizontal illuminance, a high enough vertical EML value is achieved. However, Office 2 proves otherwise, as on many measurement points there was an illuminance of over 500 lx, but an EML of under 150. One explanation for this could be the narrower beams of the luminaires in Office 2.
- The requirement for responsive lighting control (60-2) is self-explanatory, as some offices have sensors, and others do not. This was also left out from v2, but it is unlikely that it was left out because it would be too hard to achieve, as most new offices embed sensors anyway. A possible reason could be that the well-being effects of automated lighting are not evident, as they reduce the feeling of control. This could be overcome by overridable automation.
- The final feature is the brightness management (53-2), which demanded two out of four requirements to be fulfilled. Again, there were common problems with furniture brightness, but no dark ancillary spaces in any office. The difference between the ceiling of Office 1 and Office 2 was only in Office 1 having uplighting, which increases the luminance differences.

Guide for gradual improvement

There are several reasons why the management of a company would like to make renovations in an office. It could be because of the existing interior getting to the end of its life, the company moving to a new space, or aiming for savings on energy or other expenses. Whatever the reason is, the renovations almost certainly are thought as a profitable investment that will be paid back over time.

Along with the trend of well-being, ever more employers may see ever more value in investments made to enhance the well-being of the employees. This could lead to well-being being a reason to conduct renovations in an office. Still, for now, it is unlikely that a renovation would be done solely to increase well-being, but rather implementing well-being features along with a renovation that is done for other reasons.

Here, another approach is seconded by offering a tool for a more bottom-up stance. Instead of having well-being as a byproduct of a new lighting installation, the endeavor for well-being could be the starting point and driving force for change. This tool is a guide which shows the ways in which different lighting aspects can increase human well-being. The guide also helps choose solutions for real problems or real points for improvement, rather than simply accepting the arguments on which companies advertise their products. Furthermore, it supports a view of incremental enhancement, where even small steps are likely to produce more than their investment costs. Of course, in some cases the technology or circumstances do not allow other options than a full renovation, but as the case studies showed, that is not always the case.

The guide is presented in Table 16, where the leftmost column shows different well-being-related issues. These issues can potentially be mended with lighting, and the second column accordingly presents into which lighting design category the possible solution falls. The third column shows different alternatives to alleviate or fix the problem, where the first step is the easiest to perform and the last the hardest. Finally, on the rightmost column, the guide shows what are the ways through which well-being is improved by realizing the renovations.

The guide does not propose architectural changes, such as changing window materials for less glare. because their implementation is rather complicated. Some changes require trade-offs between aesthetics and well-being from light, such as altering interior decoration or repositioning workstations.

The guide presents in a simple manner what kind of gradual steps could be taken to improve well-being through lighting. Once a problem is identified, or a way of affecting well-being is determined, the most feasible step can be chosen. Then, the reference values and limits can be looked up in a lighting standard, and a professional can be consulted on how to carry out the changes. Later, if the issue persists and more resources are allocated, a more demanding alternative may be implemented.

Table 16. Guide for gradual improvement of well-being through lighting in office environment.

Issue examples	Lighting design category		Alternatives	Affects well-being by increasing ↑ / decreasing ↓
People find visual tasks demanding. People find the space gloomy.	Light levels	1	Check that the lighting is working correctly: - Luminaires are evenly lit - Control mechanisms work as intended	↑ Visual acuity ↑ Perception of space ↓ Errors ↓ Eye fatigue
		2	Provide more light: - Add supplemental lighting to workstations - Replace decoration to provide more reflectance	
		3	Renovate the lighting: - Add more or brighter luminaires	
People feel tired or have trouble sleeping.	Circadian lighting	1	Provide enough vertical light to the eyes: - Add supplemental lighting to workstations - Change decoration to provide better reflectance	↑ Alertness ↑ Circadian rhythm alignment ↑ Sleep quality ↑ Cognitive functions (learning) ↑ Mood
		2	Take advantage of lighting controls: - Add scheduled lighting patterns - Add individual controls and educate people about them	
		3	Renovate the lighting: - Add more or brighter luminaires	
People feel disturbed by artificial light.	Glare control	1	Avoid the glare: - Tilt computer screens - Rearrange workstations to head away from the light	↓ Eye fatigue ↓ Distraction
		2	Perform changes on the lighting: - Reposition the luminaires - Lower suspended luminaires	
		3	Renovate the lighting: - Replace luminaires with ones that do not produce glare	
People feel disturbed by daylight.		1	Avoid the glare: - Tilt computer screens / add tiltable computer screens - Rearrange workstations to head away from the light	↓ Eye fatigue ↓ Distraction
		2	Perform changes on shading:	

			- Add/replace blinds or curtains	
		3	Perform changes on shading: - Add accurate automatic shading	
People’s lighting preferences vary or they desire auto-mation.	Lighting control	1	Decrease effort: - Add occupancy sensors - Add daylight sensors	↑ Visual acuity ↑ Feeling of control ↑ Alertness ↑ Circadian rhythm alignment ↑ Sleep quality ↑ Cognitive functions (learning) ↑ Mood
		2	Increase feeling of control: - Add individual controls	
		3	Tunable lighting: - Add widely tunable lighting - Instruct people on how to tune the lighting for well-being benefits	
People suffer from eye fatigue.	Contrasts	1	Decrease large contrasts: - Add lighting to dark ancillary spaces	↑ Visual acuity ↑ Perception of space ↓ Fatigue ↓ Distraction
		2	Decrease large contrasts: - Change decoration colors to lighter	
		1	Provide uniform illuminance: - Add supplemental lighting	↑ Perception of space ↓ Eye fatigue ↓ Distraction
		2	Provide uniform illuminance: - Add/replace luminaires to produce less concentrated light	
People's faces seem pale.	Colors	1	Provide daylighting: - Focus human interaction to spaces where daylight is present	↑ Visual appeal of people ↑ Perception of space
		2	Renovate the lighting: - Add luminaires with a high enough color rendering index (Ra & R9)	
People suffer from headaches and migraine.	Light quality	1	Check that the lighting is working correctly: - Luminaire is not visibly flickering	↓ Headache/migraine
		2	Renovate the lighting: - Replace luminaires with ones that do not flicker	
People desire access to windows on their work-stations.	Windows	1	Introduce a policy: - Allow hot desking (no fixed workstations) - Instruct people to change workstations every now and then	↑ Visual acuity ↑ Feeling of control ↑ Alertness ↑ Circadian rhythm alignment ↑ Sleep quality ↑ Cognitive functions (learning) ↑ Mood ↑ Aesthetics
		2	Perform changes in the office layout: - Move workstations closer to windows	

The guide was composed by first identifying the different lighting design categories. The existing standards already provided their own categories, which were then unified. The same division into categories has been used in Table 8 and Table 36. The second phase was to recognize plausible problems related to each category by using the standards. These were translated to the issue examples on the first column of the guide. Then, the alternative steps for each problem were created based on the plans for changes for the offices wherever possible, and again, making use of the standards. A logical order for implementing the changes from easy to hard was sought. Finally, the ways in which the solutions affect well-being were identified using Table 1 from subchapter 2.2.2.

4.3. Recommendations for future lighting projects

Along with the trend of well-being, research topics related to lighting and well-being are certainly welcome. Regarding office lighting, it would be interesting to have quantitative research about the offices implementing well-being through lighting. There are also other spaces that could be further included in lighting and well-being research, such as schools or hospitals. Also, as new lighting technology is introduced, its impacts on well-being could make an exciting topic.

WELL certification is probably going to spread increasingly further. Research about the impact of the certification on the subjective well-being or productivity of people would be intriguing. Furthermore, the differences in well-being between offices that have implemented v1 against those that followed v2 could be researched. For those skeptical about certification, their impact on lighting design could be researched. When new de jure standards come out, their contents and influence could be reviewed as well.

5. Conclusions

This thesis aimed to help in creating an office environment where lighting improves well-being. This was planned to be done by analyzing and finding improvements for the most current, relevant and widespread standards related to office lighting and by composing a guide for office renovations to enhance well-being through lighting. The objective was pursued by conducting a literature study for theoretical knowledge on the topic and three case studies for practical data.

The literature study provided the basic research and information on the topics of lighting, well-being and standards. It was also essential to be able to critically view different standards and find their weaknesses. For some parts, the study was probably too profound. Especially examining the prevalent lighting technology in such detail did not serve the purpose of this thesis. Instead, the possibilities of future lighting technologies in improving well-being should have been emphasized.

The case studies were useful in showing ways how office lighting could fail to meet WELL v1, and how these problems could be overcome. Thus, it gave good tools on analyzing v1, especially against v2. While the case studies were valuable also for finding the steps for the guide for gradual improvement, it is hard to tell how big of an impact it had. The guide could probably have been composed even without the measurements of the case studies. Furthermore, the case studies were limited by the features of v1. Perhaps creating a custom measurement and assessment scale by combining standards would have given more objective results.

While in the very beginning it was stated that this thesis both discusses standards and builds the guide, their proportions were never determined. During the writing process, the emphasis shifted more towards standards. This was because the further WELL v1 was used and analyzed, the more evident became that it probably will have a strong effect on lighting design, and thus it had to be viewed more critically. One of the flaws of v1 was that while all the requirements were not mandatory, most of the lighting effects were treated as equal. The importance of the guide diminished even more as it became apparent that it, as well, would fail to assess the magnitude of the effects of the changes.

Yet, overall, this thesis most probably serves its purpose by giving perspective and tools to different parties for enhancing offices. Discussing standards and certificates gives lighting designers reasons to expand their view outside the traditional limits and may provide building owners with arguments to demand for better quality. The guide for gradual improvement can be useful for employers and employees to find ways to fix issues in their office environment and strive for better well-being.

References

[1] T. Huber *et al*, "Die zukunft des konsums – wie meta-services die wirtschaft umkrempeln," Zukunftsinstitut GmbH, 2013.

[2] (Cited 31 Dec 2018). *Health and wellbeing megatrends 2018*. Available: https://www.marketopportunities.fi/health-and-wellbeing-megatrends-2018.

[3] P. R. Boyce, *Human Factors in Lighting.* (Third ed.) 2014.

[4] M. Figueiro, *Non-Visual Lighting Effects and their Impact on Health and Well-Being.* 2016.

[5] R. J. Lucas *et al*, "Measuring and using light in the melanopsin age," *Trends in Neurosciences,* vol. 37, *(1),* pp. 1-9, 2014. . DOI: https://doi.org/10.1016/j.tins.2013.10.004.

[6] van Bommel, W. J. M. and van den Beld, G. J., "Lighting for work: a review of visual and biological effects," *Light Res Technol,* vol. 36, *(4),* pp. 255-266, 12/01; 2018/03, 2004.

[7] H. T. Juslén, "Mechanisms involved in enhancing human performance by changing the lighting in the industrial workplace," *Int. J. Ind. Ergonomics,* vol. 35, *(9),* pp. 843-855, 2005.

[8] H. T. Juslén, J. Verbossen and M. C. H. M. Wouters, "Appreciation of localised task lighting in shift work—A field study in the food industry," *International Journal of Industrial Ergonomics,* vol. 37, *(5),* pp. 433-443, 2007. . DOI: https://doi.org/10.1016/j.ergon.2007.01.006.

[9] M. G. Figueiro *et al*, "Circadian-effective light and its impact on alertness in office workers," *Light Res Technol,* pp. 1-13, 01/09; 2018/11, 2018.

[10] S. Hubalek, M. Brink and C. Schierz, "Office workers' daily exposure to light and its influence on sleep quality and mood," *Light Res Technol,* vol. 42, *(1),* pp. 33-50, 03/01; 2018/11, 2010.

[11] J. Denicholas, "Dimming," in *Handbook of Advanced Lighting Technology*, R. Karlicek *et al*, Ed. Cham: Springer International Publishing, 2017, pp. 445-464.

[12] S. M. Winchip, *Fundamentals of Lighting.* (Third ed.) New York: Fairchild Books, 2017.

[13] H. Juslén and L. Hellström, "Lighting meets Artificial Intelligence (AI) - a way towards better lighting," 2017.

[14] C. J. Vincent and A. Blandford, "Maintaining the Standard: Challenges in Adopting Best Practice When Designing Medical Devices and Systems," *Amia,* 2011.

[15] C. J. Vincent *et al*, "Can standards and regulations keep up with health technology?" *JMIR mHealth and uHealth,* vol. 3, *(2),* pp. e64; e64-e64, 06/03, 2015.

[16] P. M. Pattison, J. Y. Tsao and M. Hansen, "2016 DOE SSL R&D plan
U.S. department of energy," in 2016, pp. 42.

[17] W. Rhodes, "Illuminating your IQ, smart lighting market market today and future," in *Smart Lighting,* Berlin, Germany, 2015, .

[18] J. F. Waymouth, "History of light sources," in *Handbook of Advanced Lighting Technology*, R. Karlicek *et al*, Ed. Cham: Springer International Publishing, 2017, pp. 3-40.

[19] R. Karlicek *et al*, *Handbook of Advanced Lighting Technology.* Springer International Publishing, 2017.

[20] F. Rubinstein, "Adaptive control technology for lighting systems," in *Handbook of Advanced Lighting Technology*, R. Karlicek *et al*, Ed. Cham: Springer International Publishing, 2017, pp. 583-605.

[21] M. Patel and S. Mukherjee, "Lighting control protocols and standards," in *Handbook of Advanced Lighting Technology*, R. Karlicek *et al*, Ed. Cham: Springer International Publishing, 2017, pp. 559-582.

[22] L. Hellström and T. Raivisto, "Helvar Whitepaper - Connecting Controls - an overview on connectivity technologies in lighting control," 2017.

[23] DiiA, "DALI-2: The new version of the DALI standard," 2017.

[24] IES, "IES TM-23-11: Lighting Control Protocols," 2011.

[25] (Cited 31 Dec 2018). *Introducing DALI*. Available: https://www.digitalilluminationinterface.org/dali/.

[26] DiiA, "DALI Quick Start Guide," 2018.

[27] A. Pandharipande and G. R. Newsham, "Lighting controls: Evolution and revolution," *Lighting Research and Technology (2001.Print),* vol. 50, *(1),* pp. 115-128, 2018.

[28] A. Peruffo *et al*, "Lighting control with distributed wireless sensing and actuation for daylight and occupancy adaptation," *Energy and Buildings,* vol. 97, pp. 13-20, 2015. . DOI: https://doi-org.libproxy.aalto.fi/10.1016/j.enbuild.2015.03.049.

[29] B. Witzgall, "IoT lighting controls unlock new features and functionalities in specification," Cited 16 Dec 2018, 2018.

[30] (Cited 31 Dec 2018). *Dumb mistakes open smart lighting to hackers*. Available: https://www.ledsmagazine.com/articles/2016/11/dumb-mistakes-open-smart-lighting-to-hackers.html.

[31] C. Knuffke, "Human-centric lighting is the next step in LED design and control," 2017.

[32] (Cited 31 Dec 2018). *Työympäristöt*. Available: http://www.rakli.fi/toimitilat/tyoymparistot.html.

[33] M. Clarke, M. McGillivray and M. Smyth, *Understanding Human Well-being : Insights and Experiences.* 2007.

[34] World Health Organization, "Measurement of and target-setting for well-being: an initiative by the WHO Regional Office for Europe," 2012.

[35] H. Naci and J. A. Ioannidis, "Evaluation of wellness determinants and interventions by citizen scientists," .

[36] (Cited 31 Dec 2018). *Well-Being Concepts*. Available: https://www.cdc.gov/hrqol/wellbeing.htm#three.

[37] (Cited 31 Dec 2018). *List of Examples Measuring Objective Well-Beingclose*. Available: https://www.hsph.harvard.edu/health-happiness/list-of-examples-measuring-well-being/.

[38] L. Bellia, F. Bisegna and G. Spada, "Lighting in indoor environments: Visual and non-visual effects of light sources with different spectral power distributions," *Building and Environment,* vol. 46, *(10),* pp. 1984-1992, 2011. . DOI: https://doi.org/10.1016/j.buildenv.2011.04.007.

[39] J. Veitch, "Principles of healthy lighting: highlights of CIE TC 6-11's forthcoming report," 2002.

[40] G. C. Brainard and J. P. Hanifin, "Photoreception for human circadian and neurobehavioral regulation," in *Handbook of Advanced Lighting Technology*, R. Karlicek *et al*, Ed. Cham: Springer International Publishing, 2017, pp. 829-846.

[41] G. C. Brainard, "Photoreception for regulation of melatonin and the circadian system in humans," in *Fifth International LRO Lighting Research Symposium, Orlando,* 2002, .

[42] W. J. M. van Bommel, "Non-visual biological effect of lighting and the practical meaning for lighting for work," *Applied Ergonomics,* vol. 37, *(4),* pp. 461-466, 2006. . DOI: https://doi-org.libproxy.aalto.fi/10.1016/j.apergo.2006.04.009.

[43] T. A. LeGates, D. C. Fernandez and S. Hattar, "Light as a central modulator of circadian rhythms, sleep and affect," *Nature Reviews Neuroscience,* vol. 15, pp. 443, 06/11, 2014.

[44] O. Kombeiz, A. Steidle and E. Dietl, "View it in a different light: Mediated and moderated effects of dim warm light on collaborative conflict resolution," *Journal of Environmental Psychology,* vol. 51, pp. 270-283, 2017. . DOI: https://doi-org.libproxy.aalto.fi/10.1016/j.jenvp.2017.04.007.

[45] A. Steidle and L. Werth, "Freedom from constraints: Darkness and dim illumination promote creativity," *Journal of Environmental Psychology,* vol. 35, pp. 67-80, 2013. . DOI: https://doi-org.libproxy.aalto.fi/10.1016/j.jenvp.2013.05.003.

[46] A. Steidle and L. Werth, "In the spotlight: Brightness increases self-awareness and reflective self-regulation," *Journal of Environmental Psychology,* vol. 39, pp. 40-50, 2014. . DOI: https://doi-org.libproxy.aalto.fi/10.1016/j.jenvp.2013.12.007.

[47] J. A. Veitch and S. M. Kaye, "Illumination effects on conversational sound levels and job candidate evaluation," *Journal of Environmental Psychology,* vol. 8, *(3),* pp. 223-233, 1988. . DOI: https://doi-org.libproxy.aalto.fi/10.1016/S0272-4944(88)80011-2.

[48] R. Eisenberger, P. Fasolo and V. Davis-LaMastro, "Perceived organizational support and employee diligence, commitment, and innovation." *J. Appl. Psychol.,* vol. 75, *(1),* pp. 51, 1990.

[49] CEN/CENELEC, "Internal Regulations Part 3 - Principles and rules for the structure and drafting of CEN and CENELEC documents (ISO/IEC Directives — Part 2:2016, modified)," 2017.

[50] ISO/IEC, "ISO/IEC Guide 2:2004 - Standardization and related activities - General vocabulary," 2004.

[51] S. A. Bøgh and D. Standard, *A World Built on Standards: A Textbook for Higher Education.* Danish Standard Foundation, 2015.

[52] SFS, *Avain Standardien Maailmaan.* SFS, 2018, *SFS-käsikirja 1*.

[53] CENELEC, *Primer on Standards - Uncovering the Mysteries of Standardization in Europe.* CENELEC, 2002.

[54] Choi, Dong-Geun., Asia Pacific Economic Cooperation (Organization)., Secretariat., APEC Committee on Trade and Investment., Subcommittee on Standards and Conformance., Han'guk Kyugyŏk Hyŏphoe., Korea (South)., Sanŏp Chawŏnbu.,Kisul P'yojunwŏn., *Standardization : Fundamentals, Impact, and Business Strategy : Education Guideline 3 : Textbook for Higher Education.* Singapore: APEC Secretariat, 2010.

[55] CEN/CENELEC, "CEN-CENELEC Guide 17 - Guidance for writing standards taking into account micro, small and medium-sized enterprises (SMEs) needs," 2010.

[56] G. Tassey, "Standardization in technology-based markets," *Research Policy,* vol. 29, *(4),* pp. 587-602, 2000. . DOI: https://doi.org/10.1016/S0048-7333(99)00091-8.

[57] M. Orviska, "Standardization and the european standards organisations," *Central European Journal of Public Policy,* vol. 7, *(2),* pp. 36-58, 2013.

[58] ISO/IEC, "ISO/IEC Guide 2:1996," 1996.

[59] National Research Council, *Standards, Conformity Assessment, and Trade: Into the 21st Century.* Washington, DC: The National Academies Press, 1995.

[60] C. Dankers, Ed., *Environmental and Social Standards, Certification and Labelling for Cash Crops.* 2003.

[61] (Cited 31 Dec 2018). *European Accreditation*. Available: http://ec.europa.eu/growth/single-market/goods/building-blocks/accreditation/.

[62] (Cited 31 Dec 2018) Valosto, "Valaistustietoa eri lähteistä," 2017. Available: https://valosto.com/ajankohtaista/valaistustietoa-eri-lahteista/

[63] ISO/CIE, "ISO 8995:1:2002 (CIE S 008/E:2001) Lighting of work places -- Part 1: Indoor," 2002.

[64] CEN, "*EN 12464-1:2011 Light and lighting. Lighting of work places. Part 1: Indoor work places*," 2011.

[65] (Cited 31 Dec 2018). *ISO/WD TR 21783 Light and lighting - Integrative lighting - Non-visual effects*. Available: https://www.iso.org/standard/71623.html.

[66] (Cited 31 Dec 2018). *prEN 12464-1 rev Light and lighting - Lighting of work places - Part 1: Indoor work places*. Available: https://standards.cen.eu/dyn/www/f?p=204:110:0::::FSP_PROJECT,FSP_LANG_ID:61880,25&cs=16140442A02AA1837C6A7C9F6D8E08CBE.

[67] (Cited 31 Dec 2018). *CEN/TS 17165:2018 Light and lighting - Lighting system design process*. Available: https://standards.cen.eu/.

[68] (Cited 31 Dec 2018). BREEAM website. Available: https://www.breeam.com/.

[69] (Cited 31 Dec 2018). List of certificated LEED buildings. Available: https://www.usgbc.org/projects.

[70] BREEAM, "BREEAM In-Use International Technical Manual SD221 - 2.0:2015," 2016.

[71] LEED, "LEED v4 for INTERIOR DESIGN AND CONSTRUCTION," 2018.

[72] (Cited 31 Dec 20182.7.2018). International WELL Building Institute website. Available: https://www.wellcertified.com/.

[73] (Cited 31 Dec 2018). WELL v2 website. Available: https://v2.wellcertified.com/.

[74] (Cited 31 Dec 2018). *Measuring melanopic illuminance*. Available: http://lucasgroup.lab.manchester.ac.uk/research/measuringmelanopicilluminance/.

[75] Suomen Sähköurakoitsijaliitto ry and Suomen Valoteknillinen seura ry, "Valaistuksen laskenta, mittaukset ja huolto," 1996.

Appendices

Appendix A starts from page 57, Appendix B from page 61, Appendix C from page 64 and Appendix D from page 66.

Appendix A

This appendix introduces the measurement results of Office 1. Figure 6 presents the floor plan of the office with workstations and other potential measurement points mapped in it. The results in tables 17–23 are presented in the order in which they appear in the WELL Building Standard v1.

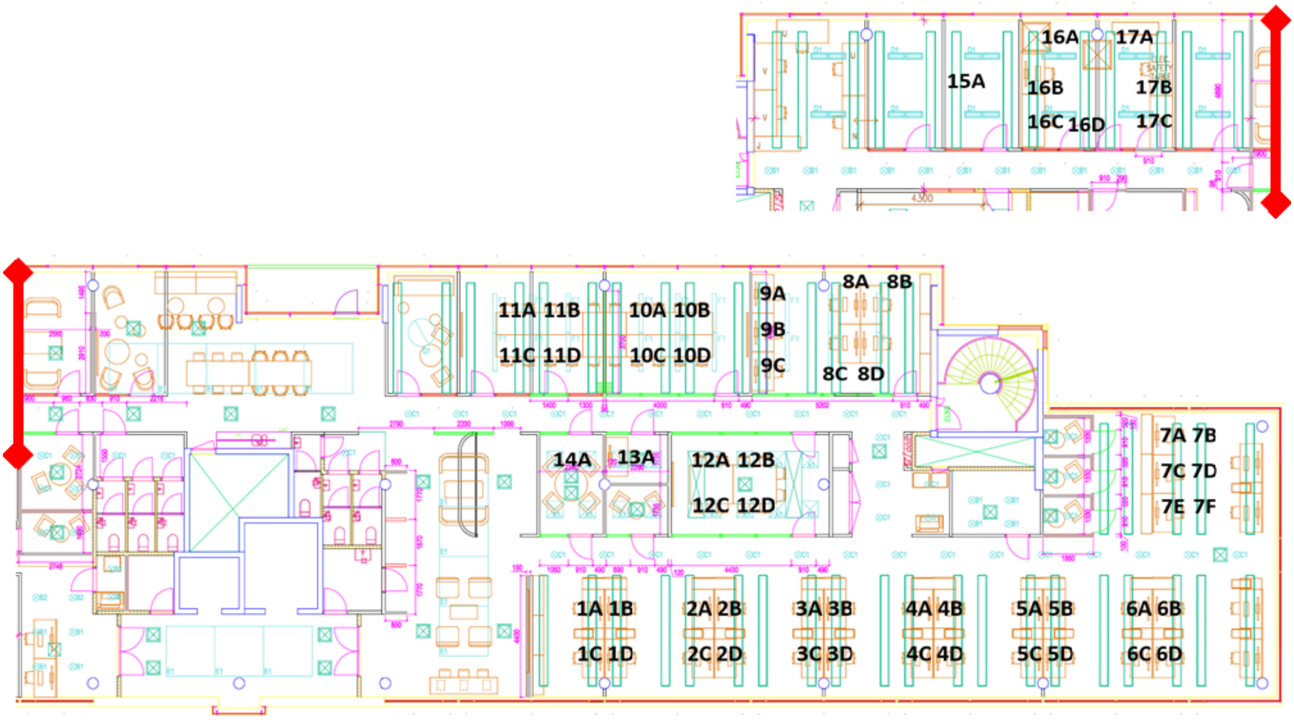

Figure 6. Office 1 floor plan with coded points of interest.

Table 17. Office 1 measurements 53-1.

Spot	Measurement No.	E_h [lx]	$E_{h,av}$ [lx]	Spot	Measurement No.	E_h [lx]	$E_{h,av}$ [lx]
1C	43	726	695	9B	61	1608	1601
	44	665			62	1595	
2A	41	816	863	10A	53	1095	1118
	42	910			54	1140	
2D	39	544	591	10D	55	1063	1118
	40	639			56	1173	
3A	37	682	723	12A	63	1362	1246
	38	765			64	1129	
3B	35	756	711	12D	65	1375	1291
	36	666			66	1206	
4B	31	763	717	13A	67	1236	1225
	32	671			68	1214	
4C	33	893	857	14A	69	611	563
	34	821			70	516	

5C	29	828	796		15A	45	786	783
	30	764				46	780	
5D	27	782	812		16B	47	919	906
	28	842				48	894	
6B	25	805	754		17A	49	784	822
	26	702				50	860	
8B	57	701	590		17C	51	903	844
	58	480				52	785	
8C	59	906	957					
	60	1007						

Table 18. Office 1 measurements and assessments 53-2.

Requirement	Measurement point	L_{min} [cd/m^2]	Measurement point	L_{max} [cd/m^2]	Ratio	Comments
Main rooms and ancillary spaces	-	-	-	-	-	Ok, as there are no dark ancillary spaces.
Task surfaces and immediately adjacent surfaces	Workstation partitions	4–18	Desk	240	13	-
Task surfaces and remote, non-adjacent surfaces in the same room	Workstation partitions	4–18	Desk	240	13	-
Two parts of the ceiling in the same room	Corners	30	Above luminaires	400–500	17	-

Table 19. Office 1 measurements 54.

Spot	Meas. No.	E_v [lx]	Melanopic ratio	EML		Spot	Meas. No.	E_v [lx]	Melanopic ratio	EML
1A	12	351	0,628	220		8D	19	442	0,731	323
1D	11	312	0,688	215		8A	20	349	0,728	254
2B	10	390	0,540	211		9A	21	307	0,684	210
3A	9	472	0,677	320		11A	17	960	0,749	719
3D	8	562	0,670	376		11D	18	835	0,795	664
4C	7	545	0,679	370		12C	22	718	0,523	375
4D	6	544	0,676	368		12B	23	816	0,510	416
5B	4	473	0,690	326		13A	24	711	0,485	345
5C	5	521	0,694	362		15A	13	235	0,655	154
6D	1	580	0,712	413		16C	14	241	0,664	160
7D	2	691	0,693	479		16A	15	208	0,695	145
7E	3	551	0,691	381		17B	16	201	0,644	129

Table 20. Office 1 measurements 55-1.

Luminaire No.	Luminaire model	L_1 [cd/m^2]	L_2 [cd/m^2]	L_3 [cd/m^2]	L_{av} [cd/m^2]	Shielding angle [°]
1	BEGA 66 874 LED	187100	524800	510900	407600	29
2	Zobra Exzite LED microprism	64420	64350	58730	62500	40
3	Zobra Exzite LED microprism	56530	48340	40790	48553	40
4	Riegens Blocks LED	25430	27110	24900	25813	30
5	Proton Galileo LED	9902	9600	11750	10417	Diffuse
6	Fagerhult Combilume	7594	10140	8500	8745	Diffuse
7	I-Valo Pro 550 LED	4536	8993	7591	7040	Diffuse
8	Pyhimys 360 mm, 600 mm,900 mm	1899	3609	8427	4645	Diffuse
9	Ensto Aino LED	4519	4750	4133	4467	Diffuse
10	Ensto Diana Flat LED	4213	4047	4022	4094	Diffuse
11	Ensto Diana Flat LED	3667	3068	3777	3504	Diffuse
12	Greenlux GLP6060	3477	3008	3464	3316	No shielding
13	Elektro-Valo Pyhimys 600 mm	3056	3104	3045	3068	Diffuse
14	Barrisol	2043	2065	1997	2035	Diffuse
15	Fagerhult Appareo	1385	1079	1155	1206	No shielding
16	Hella S104	-	-	-	-	40
17	Innojok Jasmina LED	-	-	-	-	Diffuse

Table 21. Office 1 measurements 55-2.

Spot	L over 8000	53°–90°		Spot	L over 8000	53°–90°
1A	Yes	Yes		9B	Yes	Yes
1D	Yes	Yes		9C	Yes	Yes
3A	Yes	Yes		15A	Yes	No
3D	Yes	Yes		16A	Yes	Yes
4C	Yes	Yes		16B	Yes	Yes
4D	Yes	Yes		16C	Yes	Yes
5A	Yes	Yes		16D	Yes	Yes
5B	Yes	Yes		17A	Yes	Yes
6A	Yes	Yes		17B	Yes	No
6D	Yes	Yes		17C	Yes	No
7D	Yes	Yes		11A	Yes	Yes
8A	Yes	Yes		12A	No	Yes
8C	Yes	No		13A	No	Yes
9A	Yes	Yes		14A	No	Yes

Table 22. Office 1 measurements 58.

Spot	Measurement No.	Ra	Ra_{av}	R9	$R9_{av}$		Spot	Measurement No.	Ra	Ra_{av}	R9	$R9_{av}$
1C	43	86	86	25	25		9B	61	87	87	29	29
	44	86		25				62	87		29	
2A	41	86	86	25	26		10A	53	84	84	19	19

	42	86		26	
2D	39	86	86	26	26
	40	86		26	
3A	37	84	84	17	17
	38	84		17	
3B	35	84	84	15	15
	36	84		15	
4B	31	83	83	15	15
	32	83		15	
4C	33	83	83	15	15
	34	83		15	
5C	29	84	84	16	16
	30	84		16	
5D	27	84	84	16	16
	28	84		16	
6B	25	84	83	16	16
	26	83		16	
8B	57	86	86	22	21
	58	85		20	
8C	59	85	85	20	20
	60	86		21	

	54	84		19	
10D	55	84	84	18	18
	56	84		18	
12A	63	81	81	2	2
	64	81		1	
12D	65	81	81	2	1
	66	81		1	
13A	67	80	80	-2	-2
	68	80		-2	
14A	69	92	92	62	60
	70	91		57	
15A	45	84	84	16	16
	46	84		16	
16B	47	84	84	17	17
	48	84		17	
17A	49	84	84	16	16
	50	84		16	
17C	51	84	84	15	15
	52	84		15	

The reflectance in Table 23 is calculated with Equation 4 below.

Reflectance of a perfectly diffuse reflector:

$$\rho = \frac{L\pi}{E} \tag{4}$$

where

ρ is the reflectance of the surface.
L is the luminance of the surface
E is the illuminance of the surface.

Table 23. Office 1 measurements and assessments 59.

Measurement No.	Type	Surface	E [lx]	L [cd/m^2]	Reflectance	Evaluated surface area
1	Ceiling	Concrete	142	25	55 %	20 %
2	Ceiling	Acoustic panels	144	42	92 %	30 %
3	Ceiling	Beams	126	38	95 %	15 %
4	Ceiling	Hole plates	112	28	79 %	35 %
5	Ceiling	Concrete	1462	254	55 %	20 %
6	Ceiling	Acoustic panels	572	161	88 %	30 %
7	Ceiling	Beams	180	55	96 %	15 %
8	Ceiling	Hole plates	166	45	85 %	35 %
9	Vertical	Wall	153	37	76 %	Major
10	Vertical	Wall	427	96	71 %	Major
11	Vertical	Wall	348	84	76 %	Major

12	Vertical	Wall	367	105	90 %	Major
13	Vertical	Church wall	988	42	13 %	Medium
14	Vertical	Church wall	1088	100	29 %	Medium
15	Vertical	Church wall	1084	50	14 %	Medium
16	Vertical	Cable cover	380	101	84 %	Minor
17	Vertical	Columns	756	175	73 %	Minor
18	Vertical	Window frames	319	8	8 %	Minor
19	Furniture	Shelves	342	92	85 %	Major
20	Furniture	Desks	904	285	99 %	Major
21	Furniture	Grey desk partition	1517	115	24 %	Medium
22	Furniture	Blue desk partition	1509	25	5 %	Medium
23	Furniture	Red desk partition	1475	27	6 %	Medium
24	Furniture	Chair	539	8	5 %	Minor
25	Other	Floor	416	25	19 %	100 %

Appendix B

This appendix introduces the measurement results of Office 2. Figure 7 presents the floor plan of the office with workstations and other potential measurement points mapped in it. The results in Table 24–29 are presented in the order in which they appear in the WELL Building Standard v1.

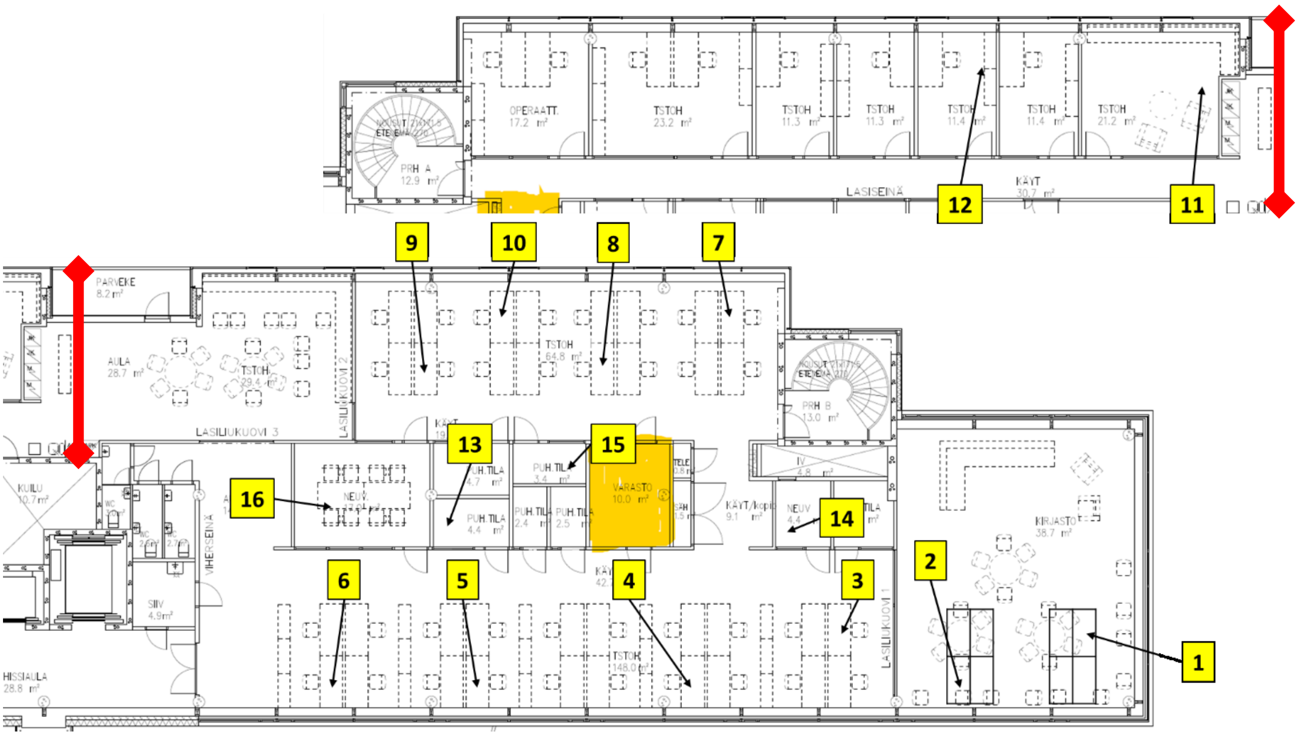

Figure 7. Office 2 floor plan with coded points of interest.

Table 24. Office 2 measurements 53-1.

Spot	Measurement No.	E_h [lx]	$E_{h,av}$ [lx]
1	1	277	269
	2	260	
2	3	641	612

Spot	Measurement No.	E_h [lx]	$E_{h,av}$ [lx]
9	17	586	628
	18	669	
10	19	262	283

	4	583			20	303	
3	5	782	773	11	21	344	336
	6	763			22	328	
4	7	221	211	12	23	408	380
	8	201			24	351	
5	9	515	559	13	25	1155	1172
	10	602			26	1188	
6	11	256	230	14	27	878	864
	12	203			28	849	
7	13	606	587	15	29	1276	1253
	14	567			30	1230	
8	15	775	780	16	31	329	335
	16	784			32	340	

Table 25. Office 2 assessments 53-2.

Requirement	Subjective evaluation
Main rooms and ancillary spaces	There are no dark ancillary spaces in the office.
Task surfaces and immediately adjacent surfaces	The luminance difference between black desks and light floor seems too high.
Task surfaces and remote, non-adjacent surfaces in the same room	The luminance difference between black workstation partitions and white walls seems too high.
Two parts of the ceiling in the same room	The ceiling seems uniform.

Table 26. Office 2 measurements 54.

Spot	Measurement No.	EML	Spot	Measurement No.	EML
1	33	123	9	41	140
2	34	195	10	42	144
3	35	110	11	43	148
4	36	115	12	44	189
5	37	83	13	45	288
6	38	97	14	46	298
7	39	250	15	47	397
8	40	245	16	48	120

Table 27. Office 2 measurements 55-1.

Luminaire No.	Description	Shielding angle [°]
1	Workstations	> 30
2	Corridors	Diffuse
3	Meeting rooms and booths	Diffuse

Table 28. Office 2 measurements 58.

Spot	Measurement No.	Ra	Ra_{av}	R9	$R9_{av}$	Spot	Measurement No.	Ra	Ra_{av}	R9	$R9_{av}$

1	49	86	86	28	28
	50	86		28	
2	51	82	83	17	18
	52	83		18	
3	53	81	81	9	9
	54	81		8	
4	55	83	83	15	16
	56	83		16	
5	57	81	81	10	10
	58	81		9	
6	59	83	83	15	16
	60	83		17	
7	61	82	82	13	14
	62	82		14	
8	63	81	81	9	9
	64	80		8	

9	65	81	81	12	13
	66	81		14	
10	67	85	85	25	24
	68	84		23	
11	69	86	86	27	33
	70	86		38	
12	71	92	91	52	46
	72	89		40	
13	73	82	82	3	3
	74	82		2	
14	75	82	82	3	3
	76	82		3	
15	77	82	82	3	3
	78	82		3	
16	79	84	84	13	13
	80	84		13	

The reflectances in Table 29 and Table 35 is calculated with Equation 5 below. [75]

$$\rho = \frac{E_{out}}{E_{in}} \tag{5}$$

where

ρ is the reflectance of the surface
E_{out} is the illuminance measured by facing the lux meter towards the surface
E_{in} is the illuminance measured by facing the lux meter away from the surface.

Table 29. Office 2 measurements and assessments 59.

Measurement No.	Type	Surface	E [lx]	L [cd/m^2]	Reflectance	Evaluated surface area
81	Ceiling	Concrete	-	-	-	Major
82	Vertical	White wall	1342	951	71 %	Major
83	Vertical	Yellow sound wall	1331	615	46 %	Minor
84	Vertical	Green sound wall	127	28	22 %	Minor
85	Vertical	Green curtain	378	98	26 %	Minor
86	Vertical	Black desk partition	223	108	48 %	Minor
87	Furniture	Desk	1258	150	12 %	Minor
88	Furniture	Desk wall	393	284	72 %	Minor
89	Furniture	Meeting room table	280	29	10 %	Minor
90	Other	Yellow floor	896	249	28 %	Minor
91	Other	Grey floor	225	78	35 %	Major
92	Other	Green floor	615	108	18 %	Minor

Appendix C

This appendix introduces the measurement results of Office 3. Figure 8 presents the floor plan of the office with workstations and other potential measurement points mapped in it. The results in Table 30–35 are presented in the order in which they appear in the WELL Building Standard v1.

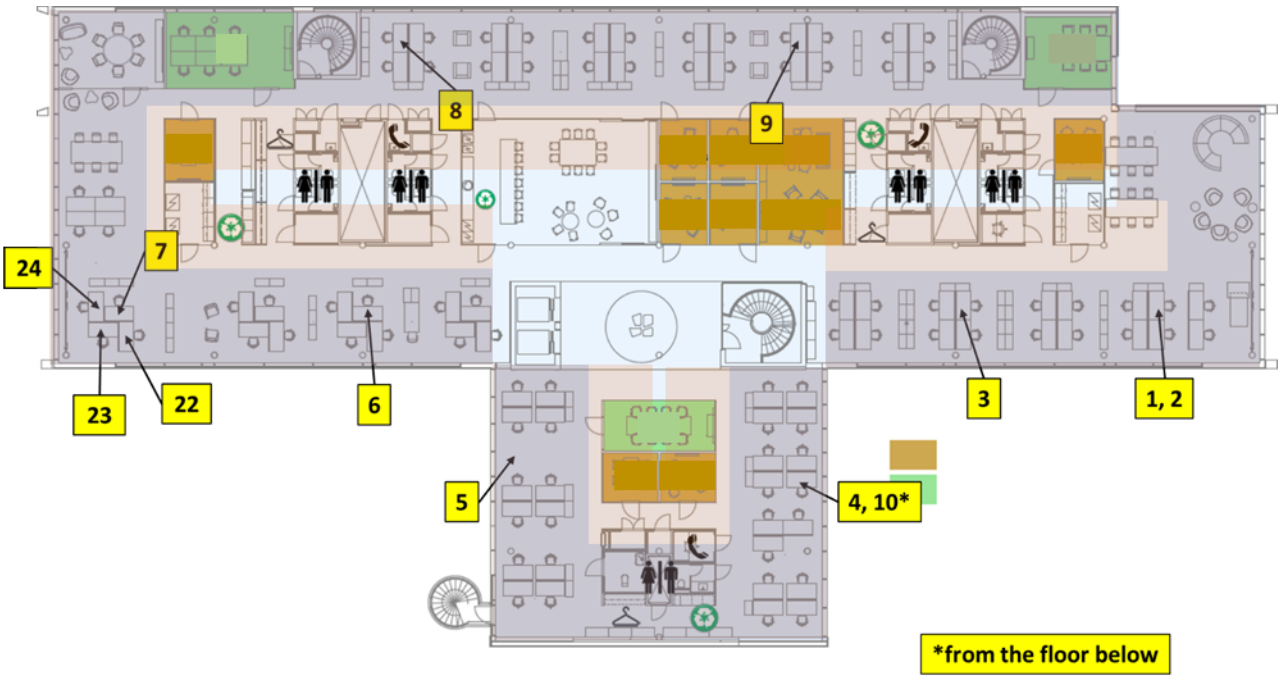

Figure 8. Office 3 floor plan with coded points of interest and areas at distances of 7,5 m and 12,5 from windows.

Table 30. Office 3 measurements 53-1.

Spot	Measurement No.	E_h [lx]	$E_{h,av}$ [lx]	Spot	Measurement No.	E_h [lx]	$E_{h,av}$ [lx]
1	1	882	903	8	17	1015	1033
	2	923			18	1051	
2	3	934	920	9	19	918	909
	4	905			20	900	
3	5	655	632	10	21	856	901
	6	608			22	946	
4	7	681	667	22	23	717	736
	8	653			24	754	
5	9	637	685	23	25	936	936
	10	732			26	935	
6	11	781	785	24	27	723	769
	12	789			28	814	
7	13	792	782				
	14	771					

Table 31. Office 3 assessments 53-1.

Requirement	Subjective evaluation

Main rooms and ancillary spaces	There are no dark ancillary spaces in the office.
Task surfaces and immediately adjacent surfaces	The luminance difference between white desks and dark workstation partitions seems too high.
Task surfaces and remote, non-adjacent surfaces in the same room	The luminance difference between dark workstation partitions and white walls seems too high.
Two parts of the ceiling in the same room	The ceiling seems uniform.

Table 32. Office 3 measurements 54.

Spot	Measurement No.	EML		Spot	Measurement No.	EML
1	29	462		8	35	527
2*	-	-		9	36	415
3*	-	-		10	37	290
4	31	382		22	38	351
5	32	221		23	39	328
6	33	454		24	40	394
7	34	450				
*Values missing due to failure in documentation.						

Table 33. Office 3 measurements 55-1.

Luminaire No.	Description	Shielding angle [°]
1	Workstations	> 30
2	Corridors	Diffuse
3	Other tables	Diffuse

Table 34. Office 3 measurements 58.

Spot	Measurement No.	Ra	Ra_{av}	R9	$R9_{av}$		Spot	Measurement No.	Ra	Ra_{av}	R9	$R9_{av}$
1	41	82	82	23	23		8	55	88	88	43	41
	42	82		23				56	87		38	
2*	43	-	-	-	-		9	57	87	88	39	41
	44	-		-				58	88		43	
3	45	82	82	21	21		10	59	84	84	16	16
	46	82		21				60	84		16	
4	47	86	87	35	37		22	61	83	83	29	29
	48	87		38				62	83		28	
5	49	87	87	36	35		23	63	90	90	47	45
	50	86		34				64	89		43	
6	51	82	82	22	22		24	65	84	84	30	30
	52	82		22				66	84		29	
7	53	84	84	27	27		*Values missing due to failure in documentation.					
	54	83		26								

The reflectance of measurement 3 in Table 35 is calculated with Equation 5. [75]

Table 35. Office 3 measurements and assessments 59.

Measurement No.	Type	Surface	E [lx]	L [cd/m^2]	Reflectance	Evaluated surface area
1	Ceiling	Panel	-	-	High	Major
2	Vertical	Wall	198	159	80%	Major
3	Vertical	Black wall	-	-	Low	Medium
4	Furniture	Desk partition	-	-	Low	Major
5	Furniture	Desk	-	-	High	Major
6	Furniture	Black shelf	-	-	Low	Minor
7	Other	Floor	-	-	Low	Major

Appendix D

This appendix elaborates the lighting requirements of each standard referred to in this thesis. The requirements of the standards have been unified into subcategories, which are then grouped into categories and presented in Table 36.

Table 36. The lighting requirements of five different standards, unified into categories.

Category	Subcategory	EN	BR	LE	v1	v2
Light levels	Illuminance level	x	o		x	x
	Consideration of different tasks	x	o			x
	Consideration of different ages					x
Circadian lighting	Circadian illuminance level				x	o
	Circadian scheduling					
Glare control	UGR value	x				o
	Luminaire shielding angle	x			x	o
	Luminance limits for viewing angles	x		o	x	o
	Amount of direct-only overhead luminaires			o		
	Light emitted only above the horizontal plane					o
	Luminaires do not produce glare on screens	x			o	
	Tiltable computer screens				o	
	Solar glare prevention	x			x	o
	Shading	x	o			
	Not 24/7-shading		o			o
	Automated shading				o	
Lighting control	Luminaire zoning		o	o	x	
	Occupancy sensors		o		o	
	Daylight sensors		o		o	
	Manually overridable sensors		o			
	Tunable lighting					o
	Allowing occupants to control the lighting			o		
	Allowing occupants to tune the lighting					o
	Control interface location and line of sight			o		
Contrasts	Contrasts (luminance) between surfaces and spaces	x			x	o
	Illuminance uniformity	x				
	Illuminance uniformity on work plane					o

	Illuminance ratio between surfaces			o		
	Transition time in light level changes					o
Reflectance	Surface reflectance	x		o	o	
Colors	Color rendering index	x		o	o	o
Sunlight	Yearly amount of sunlight			o	o	o
Others	Distance to outside view windows				o	o
	Window transmittance				o	o
	Transmittance uniformity				o	
	Window-wall ratio				o	o

x = mandatory or not defined requirement
o = optional requirement
EN = EN 12464 1:2011 Light and lighting. Lighting of work places. Part 1: Indoor work places,
BR = BREEAM
LE = LEED
v1 = WELL Building Standard v1
v2 = WELL Building Standard v2